

Sustainable Food Systems from Agriculture to Industry

Improving Production and Processing



Edited by Charis M. Galanakis



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SUSTAINABLE FOOD SYSTEMS FROM AGRICULTURE TO INDUSTRY

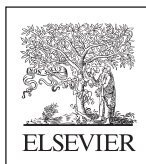
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CHARIS M. GALANAKIS



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PREFACE

Until the end of the 20th century, food loss and disposal of food waste were not evaluated as matters of concern. The prevalent policy mainly aimed at increasing food production, without improving the efficiency of the food systems. This fact increased the generation of food lost or wasted along food supply chains. In the 21st century, escalating demands for processed foods have required identification of concrete opportunities to prevent depletion of natural resources, restrict energy demands, minimize economic costs, as well as reduce food losses and food wastes. Besides, recent changes in the legislative frameworks and environmental concerns have stimulated the industry to reconsider their management policy and in some cases to face the concept of “recovery” as an opportunity.

This tendency is becoming a major concern for the food industry around the world, as resources become more restricted and demand grows. Indeed, food industry is increasing its attention toward sustainability, which has been developed into a trendy word, characterizing a frame of advances and modernization in the years to come. However, sustainability is neither easy to specify nor to implement. In theory, it reflects the principle that we must meet the needs of the present generation without compromising the ability of future generations to meet their own needs. For instance, food processing ensures that the resources required to produce raw food materials and ingredients for food manufacturing are used most efficiently. Responding to this goal, sustainability requires the maximum utilization of all raw materials produced and integration of activities throughout all the stages of production and consumption. To maximize the conversion of raw materials into consumer products, efforts begin at the production stage, with activities to reduce postharvest losses and to increase the use of by-product streams (wastes). Efforts continue, through food manufacturing and beyond, to ensure that energy, water, and other resources are used most efficiently and environmental impacts are minimized. Refrigeration of fresh produce is an example of an action that reduces loss and increases the edible life of the product.

Subsequently, there is a need for a new guide covering the latest developments in this particular direction. The present book

fills this gap by providing certain solutions for industrial sustainability in spite of processing, production, and waste management. It covers important aspects of the sustainable food production and processing, at all relevant stages.

The book consists of three parts and 12 chapters. Part A (*Sustainable Food Production*) includes five chapters. [Chapter 1](#) provides an overview of the current food production methods and describes the options for making healthier foods with reduced environmental impact. [Chapter 2](#) highlights the importance of earthworms and reveals their role in sustainable agriculture, whereas [Chapter 3](#) elucidates the use of local plants and animals for food production, reflecting many challenges related to the industrial and sustainable use of biological resources. [Chapter 4](#) evaluates the environmental, economic, and social sustainability of agro-food systems through life cycle approaches, whereas [Chapter 5](#) explores the sustainability and corporate social responsibility in the food supply chain. Part B deals with *Sustainable Food Processing* in four Chapters. [Chapter 6](#) analyzes energy saving in food processing through the use of innovative technologies (e.g., in pasteurization, sterilization, extraction, evaporation, and so on). [Chapter 7](#) focuses particularly on sustainable drying and chilling/freezing methods of perishable foods in the organic sector to maintain their high nutritional values. [Chapter 8](#) discusses the existing and alternative packaging solutions, with an ultimate goal of denoting weaknesses and opportunities to improve sustainability and efficiency of the food sector. [Chapter 9](#) describes sustainable cleaning in the food industry, highlighting the efficacy of Electrolyzed Water as an interesting and ecological clean-in-place reagent, whereas [Chapter 10](#) explores the possibilities of applying microbial biosurfactants in food sanitation. Finally, Part C (*Sustainable Food Waste Management*) consists of two chapters ([Chapters 11](#) and [12](#)) dealing with food waste reduction and valorization, respectively.

In conclusion, the ultimate goal is to inspire the scientific community, professionals, and enterprises that aspire to optimize the efficiency of food systems and reduce environmental impact of involved industries. It is intended to support researchers, specialists, agriculturalists, chemical engineers, professionals, and strategy developers working in the agro-food industry, from farm to fork. It could be purchased by University libraries and Institutes all around the world to be used as a textbook and/or ancillary reading in graduate and postgraduate level multidiscipline courses dealing with sustainable food systems, agricultural and environmental science, food processing, bioresource valorization, and chemical engineering.

I would like to take this opportunity to thank all the contributors of this book for their fruitful collaboration and high-quality work in bringing together issues of food production, food processing, and food waste management in an integral and comprehensive text. I consider myself fortunate to have had the opportunity to collaborate with so many knowledgeable colleagues from Germany, Italy, India, Iran, Norway, Poland, Portugal, Romania, Turkey, United Kingdom, and United States. Their acceptance of editorial guidelines and book concept is highly appreciated. I would also like to thank the acquisition editor Nancy Maragioglio for her honorary invitation to lead this project and all the production team of Elsevier, specifically Barbara Makinster and Anusha Sambamoorthy for their assistance during the editing and in press process, respectively.

Last but not least, a message for the reader. In a collaborative project of this size, it is impossible for it to not contain any errors. Thus, if you find errors or have any objections, I would really appreciate if you contact me.

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PART

A

SUSTAINABLE FOOD PRODUCTION

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INTRODUCTION TO SUSTAINABLE FOOD PRODUCTION

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1 Introduction

Historically, man has always sought his dominion over nature. The set of techniques used to grow plants for food, beverages, fiber, energy, raw material for clothes and construction, medicines, tools, or just for aesthetics contemplation is part of agriculture. Agriculture is the science, art, or practice of cultivating the soil, producing crops, and/or raising animals at different levels for marketing or for own consumption (Merriam-Webster, 2016). The very definition of agriculture is broad and refers to the most basic instincts of human beings such as the ability to produce food to satisfy his hunger and for the survival of the species. The etymology of the word agriculture comes from the Latin *agricultūra* “cultivation of the land,” composed of *ager* (field, territory) and *cultūra* (cultivation, growing), in the strict sense of cultivation. The history of agriculture is closely linked with human history, due to its importance in path followed by the human life, as the emergence of agriculture separates the Neolithic period from the immediately previous age, which was the period of the chipped stone (Alexandratos et al., 2006).

With the emergence of agriculture and the man shaping nature in his favor begins the development of new techniques, tools, and consequently the possibility of small settlements, which was previously impossible because the man was essentially hunter and

collector following the preys where the go. Therefore, the itinerant and nomad nature of man is changed and a new era begins.

The locations indicated in Fig. 1 show where the first regions of agricultural production were identified (Ladizinsky, 1998):

- (1) Mexico-Guatemala,
- (2) Peru-Ecuador-Bolivia,
- (2A) Southern Chile,
- (2B) Southern Brazil,
- (3) Mediterranean,
- (4) Middle East,
- (5) Ethiopia,
- (6) Central Asia,
- (7) Indo-Burma,
- (7A) Siam-Malaya-Java,
- (8) China and Korea.

From the analysis of these sites, it can be seen that these locations subsequently formed the basis for large societies, thus demonstrating how the evolution of agriculture has affected and changed humankind and how it generally shaped is our society.

The people who created and mastered new tools had an advantage compared with those who did not have this same capability and as today productivity is of paramount importance, more than just an economic advantage as it was and is still a strategic advantage.



Fig. 1 First regions of agricultural production (centers of origin identified by Nikolai Vavilov (Ladizinsky, 1998).

With the evolution of tools and techniques and with the increasing use of animal power in agricultural production (see Fig. 2), an increase in productivity was achieved, making the societies that mastered the techniques grow more than others and became empires and superpowers at their time.



Fig. 2 Daily scenes of agricultural production in Egypt (note the use of animal force to ensure greater productivity) (Seidel & Shedid, 1991).

The agricultural production system underwent a large evolution during the Industrial Revolution. At approximately the same time, Great Britain was undergoing an agricultural revolution. This revolution was caused by the implantation of new tools, by the use of fertilizers (a new technology at the time) and new techniques of planting, resulting in a very significant increase of labor and land productivity. The evolution of the major commodities (weight and price) during this period is shown in [Fig. 3](#).

[Fig. 4](#) shows the farming area in Great Britain during that same period: the increase in agricultural production was $\sim 340\%$, while the cultivated area decreased $\sim 2\%$.

This outstanding increase in production despite maintaining practically the same cultivation area is explained by the several techniques and tools created during that period. Productivity values experienced a sharp increasing trend.

However, this productivity increase had consequences attached. The environmental impact that, before the Agricultural Revolution, was practically zero, increased with the use of fertilizers, machines with burning of fossil fuels, deforestation, mining, and other activities. According to Intergovernmental Panel on Climate Change (IPCC), these activities lead to the increase of the global warming.

These human activities result in a high degree of concentration of greenhouse gases (GHGs) (CO_2 , CH_4 , N_2O) in the atmosphere since the beginning of the Industrial Revolution around 1750 ([Parry et al., 2007](#)). Carbon dioxide (CO_2) in the atmosphere increased from 280 parts per billion per volume (ppb) to an outstanding value of 379 ppb since the preindustrial revolution era to 2005. The same applies to methane (CH_4) concentrations. This increase was even more significant since the increase of its atmospheric concentration was $\sim 250\%$, from 715 to 1774 ppb over the same period. Nitrous oxide (N_2O) had an atmospheric concentration of ~ 270 ppb before the Industrial Revolution, and increased to 319 ppb in 2005 ([Parry et al., 2007](#)).

Climate change poses various difficulties and aggravates the shortage of availability of drinking water on the surface of the planet. This increasing problem is due to significant changes and variables affecting the normal water circle, which would be precipitation, infiltration, runoff, evaporation, and condensation. The shift of the rainfall season in some places that previously had well-defined seasons of drought and rain had significant consequences on the local environment.

The quality of surface water also declined, which represents only 0.006% of the total volume of water in the planet. This is a direct consequence of the chemical inputs into the air, of the

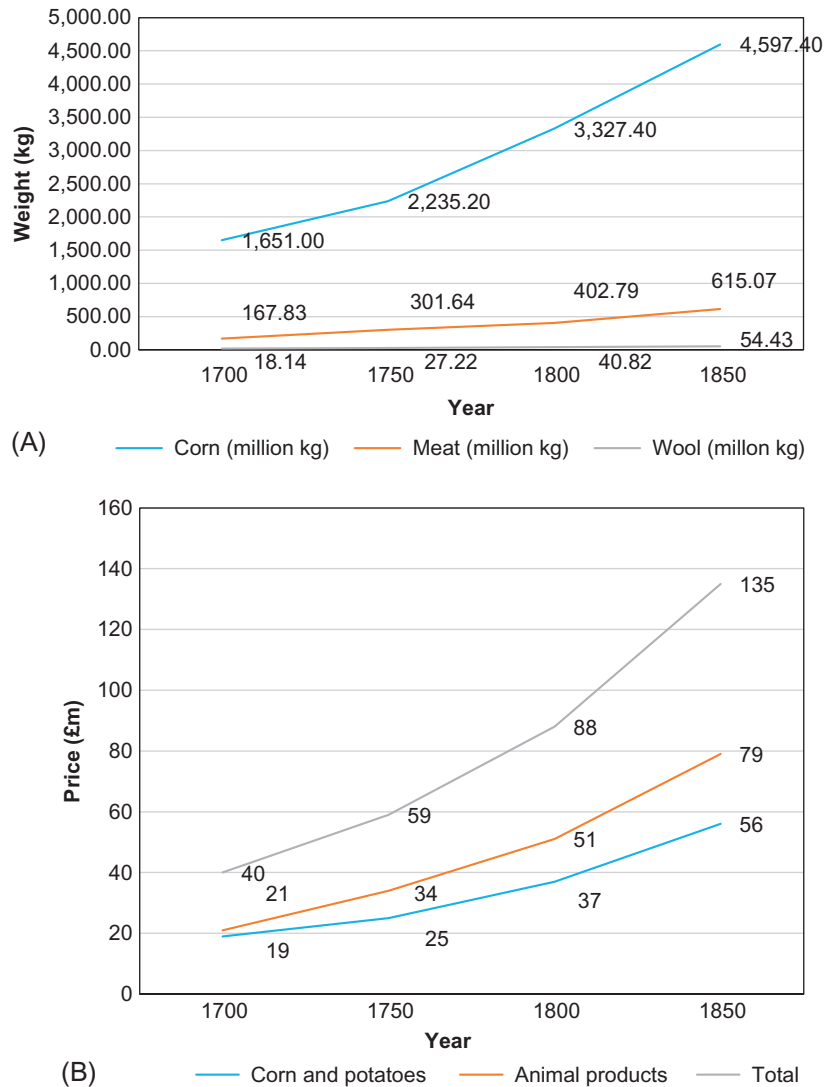


Fig. 3 Evolution of major commodities (weight and price) in Great Britain during the Agricultural Revolution: wheat, oats, beans, and turfs; seed nectar and oats are included in maize. Meat, wool, dairy products, and cheese are included in animal production) (Allen, 1994). (A) Increase in the production of major commodities and (b) increase in the price of major commodities.

environment where it is located, and of the biochemical processes that these inputs transform within the system itself. The inputs are from natural processes and/or human activities, such as the atmospheric deposition in the course of the aquatic system or direct discharge of pollutants in the watercourses, and direct

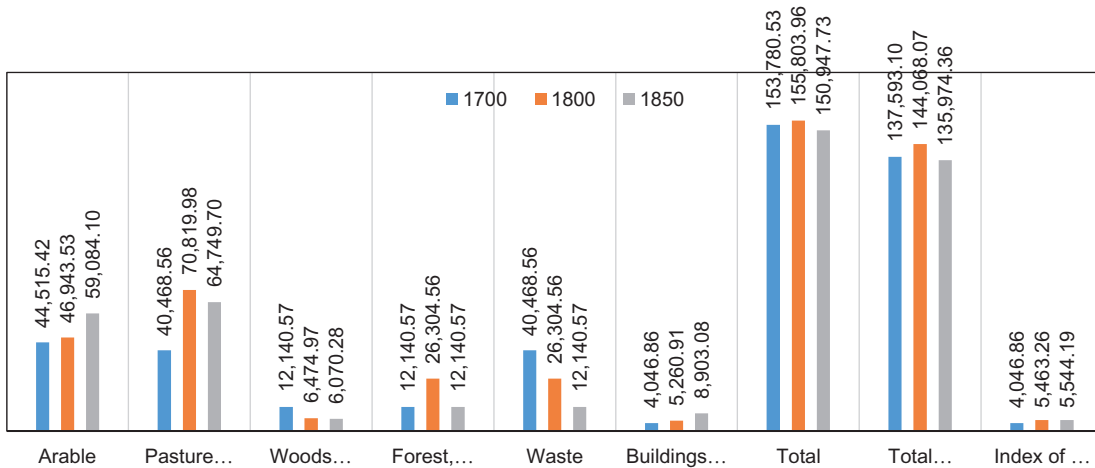


Fig. 4 Distribution of the farming area in Great Britain during the Agricultural Revolution—utilization of English and Welsh land (km²) (Allen, 1994).

chemical injections of pollutants into the aquatic system (Anderson et al., 2011). The water flows into the river basins through several types of vegetation, soils, and ecosystems, contributing each one to extract, add or chemically transform it before reaching a stream. Although, the opposite can also happen, this water can chemically alter the region that it bathes. The path that the hydrological flow that water takes through the natural course of the river basins, and the resulting transformations that occur along that route will determine its chemical and physical characteristics when entering the surface water system (Anderson et al., 2011). The changes in the region's hydrological system are not only local but can and probably will be broader as chemical changes in water follow their natural course.

In agriculture, pesticides are a major polluter of aquifer systems. The literature review concerning the use of pesticides estimates that commercial pesticide runoff losses in agricultural fields are around 0.5% or less of the quantities initially applied, unless severe precipitation occurs between 1 or 2 weeks after its application. Exceptions are related to the application of organochlorine insecticides, as the aquifer systems may absorb about 1%, regardless of the climatic pattern, due to their long persistence in the production fields. The chemical formulations of wettable powder herbicides applied to the soil surface can be lost up to 5%, depending on the time and inclination of the terrain, due to the ease of powder removal (Wauchope, 1978).

The behavior and the destination of the pesticide losses are usually unknown and it is necessary to be studied. Thus, information on the factors such as the time and distance that this pesticide can affect the capacity of a certain ecosystem must be determined. The ability of the local ecosystem to recover from a transient pesticide concentration and its dissipation capacity in the local aquatic ecosystem should also be studied.

Meanwhile, the livestock sector has always been and always will be a strategic sector, because it is directly connected to the human race survival. Although the richness of farming products has declined over the last decade (today the sector accounts for about 4% of the world's GDP), it still amounts to about US \$3125 billion per year.

The impact that the agricultural sector has on our planet goes far beyond the deforestation for the cultivation of crops. This procedure has consequences on thousands of animals and plants, reducing the number of trees (being this condition directly linked to global warming), saturating land due to the effects of the continuous planting of the same crop on the land, particularly on the losses of specific nutrients, and including chemical pollution with the use of agrochemicals. Therefore, balancing the productivity increase with the environmental cost is a current discussion on the several productive sectors of the agriculture, since each action field has its own characteristics, which are very different from each other. Therefore, it is necessary to study the intrinsic characteristics of each productive sector, since for example, the livestock production has not the same techniques, machinery, and tools as the cereal production sector.

Thus, studying each field of agricultural production separately is inevitable, mainly due to the enormous production process and product chain differences. In this way, the next section describes separately the main agricultural sectors, for example, the sectors that have more worldwide production and the highest overall market value.

2 Cereals Sector

Cereal production accounts for a large part of world agricultural production. According to FAO, the world cereal production was expected to reach 2571 million tons in 2016, which is ~16.7% higher than the production obtained in 2015, although well below the target of 3.0 billion tons expected by 2050 (Alexandratos & Bruinsma, 2003).

Cereals (corn, rice, and wheat) account for more than 50% of the calories that a human normally eats throughout the day

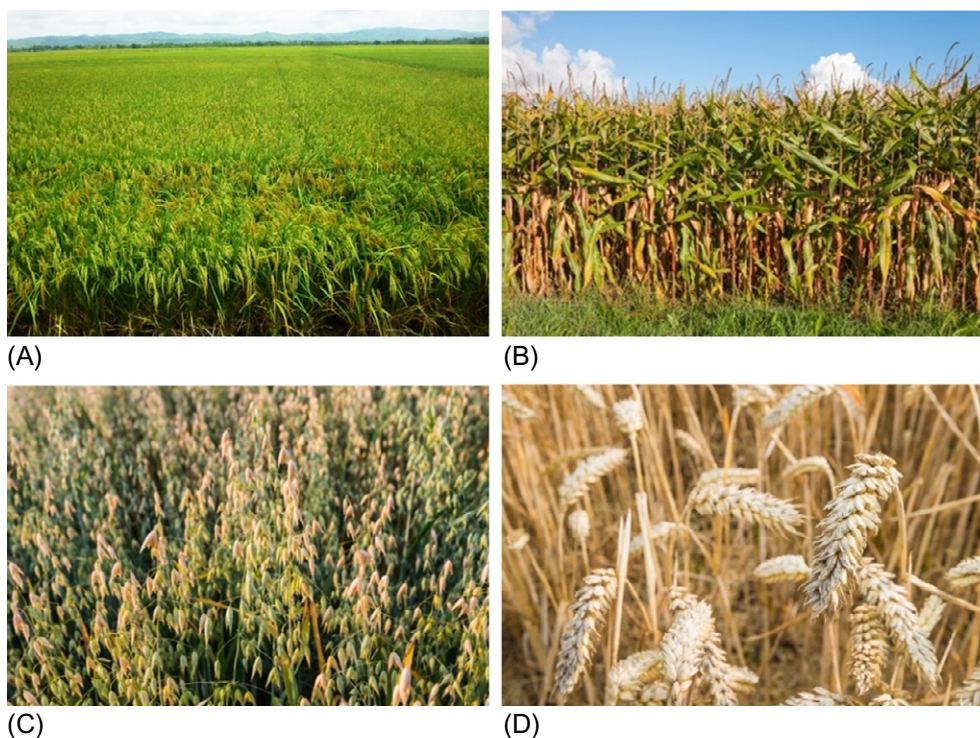


Fig. 5 Different types of cereal plantations: (A) Rice fields, (B) Corn plantation, (C) Oats plantation, and (D) Wheat plantation. (A) From @RahmatNugroho/123RF.com; (B)–(D) From @Ruud Morijin/123RF.com.

(see examples of these kinds of plantation in Fig. 5). Therefore, cereals are the food base for most populations around the globe. The increase of production can no longer depend on an intensive supply of inputs, such as the increased use of agrochemicals.

Soil degradation and toxin accumulation in rice production systems is already a reality in Asia and a cause for concern due to the slowdown in productivity growth. Thus, the intensive use of pesticides to ensure productivity increase will not guarantee an increase in productivity.

Techniques have been developed to ensure an increase in productivity without the introduction of new inputs. In China, it was found that applying a genetically diverse rice variety in the same paddy reduced significantly the incidence of fungal diseases, so farmers were able to avoid the application of fungicides which besides reducing costs reduced the environmental impact. Another example is related to farmers in Zambia who grow acacia trees, *Faidherbia albida*, near their cornfields. They use the acacia

leaves, rich in nitrogen, as a natural fertilizer and as a protective vegetable cover during the rainfall season. These farmers managed to triple their yields with this relatively simple and inexpensive technique (Garrity et al., 2010).

There are even more techniques and production systems that seek to maximize the agricultural production, combining good energy performance and low environmental costs. These opportunities, as stated, are not exclusive to the cereals sector.

Chinese farmers receive governmental incentives to invest in clean production plantations, that is, without environmental impacts or at least with mitigated impacts. The lack of knowledge about these incentives is the major problem for adherence. Only 21 farmers of the 259 farmers surveyed used the incentives. In all, 174 farmers claimed that they did not know the incentive program and 64 farmers pointed out their lack of technical knowledge (Luo et al., 2014).

Climate change affects cereal production in a variety of ways such as long periods of drought or rain, extremely harsh winters and scorching summers, and plagues on crops. According to Garrick and Liburd (2017), climate change can cause variation of weather events that may increase the CO₂ concentration and the global temperatures. Pest development is highly influenced by environmental factors such as temperature. As temperature rises, it becomes more conducive to pest development and its geographical scale of influence becomes larger. As populations of pests' increase, natural control programs focused primarily on the direct application of pesticides to sprays had to evolve to a greater management and efficiency. The uncontrolled application of pesticides can cause several problems, such as altering the chemical properties of the soil, which can make it less profitable or reduce its capacity to produce as before.

There should be government programs for pest control. These programs should cover a local sphere of production and rely on the cooperation of local associations and cooperatives, private industry (pest control and agrochemical companies), and the public in general that deals with the problem daily (Garrick & Liburd, 2017).

The indiscriminate use of pesticides can be a double-edged sword because it may lead to entering a cycle of increasing use of pesticides, thus causing a greater environmental impact. In addition, the greater application of pesticides may cause lower agricultural production due to soil characteristics modification, thus requiring a greater amount of fertilizer. The sum of greater application of pesticides and fertilizers can have relevant negative impacts on the environment, causing more emissions of GHGs,

contributing to the increase in the global temperature, which in the last instance will finally promote a higher incidence of pests. Consequently, rising temperatures due to climate change will strongly affect economic growth around the world, not only of farmers but also of all kinds of business.

3 Livestock Sector

Another large sector of the agroindustry is the livestock sector for activities related to animal husbandry or animal agriculture. The word livestock has a Latin origin Pecus means “head of cattle” (see Fig. 6) and has the same Latin root of pecunia (coin, money). In ancient Rome, animals raised for slaughter were also used as a monetary value stored.

The livestock sector nowadays covers several types of products from food to clothing, although the sectors with more emphasis are meat (bovine, pork, ovine, caprine, poultry, etc.), eggs, milk, and honey because these are sectors that generate greater income. The secondary sectors are leather, wool, and silk, the use of animal power to perform work and even dry manure as fertilizer and food preparation. Thus, the scope and field of action of livestock farming is gigantic, increasing the difficulty of evaluating the general environmental costs or their ecological footprint. As each production system has its particularities, likewise in other sectors of agriculture, the study of the ecological footprint must be done on a case basis.

Although it is well known that occidental societies eat much more meat than needed, the worldwide consumer preference regarding the use of meat in their diet continues to increase.



Fig. 6 Brown cows “head of cattle.” From @VasutaThitayarak/123RF.com.

The global production of meat is expected to reach 470 million tons in 2050, more than the double of the 229 million tons verified in 1999/2001 (Nigel et al., 2010).

Currently, meat product industries play a major role in many global economies and, in many countries, it is the industry with a higher economic weight within the food industries. The types of meat most produced and consumed, at both international and national level, are beef, pork, and poultry. According to Silva et al. (2016), the worldwide most per-capita consumed type of meat is pork (15.8 kg/year), followed by poultry (13.6 kg/year), and finally by beef (9.8 kg/year).

The amount of drinking water for consumption of livestock: cows, pigs, sheep, and chickens in intensive farming were calculated, respectively, at 103, 17, 9, and 1.3 to 1.8 L/day. Approximately 8, 4, and 1 kg of cereals are needed to produce 1 kg of bovine, porcine, and poultry meat, respectively (Alexandratos et al., 2006). Therefore, although poultry production is the highest energy efficient, it is still the most energy demanding in cereal production.

The ruminant livestock has one more aggravating factor in relation to the other types of livestock, that is enteric fermentation. Enteric fermentation is the digestive process that occurs in the rumen of ruminant herbivorous cattle (bovine, ovine, and caprine). The result of this biological process is the CH₄ gas, a large enhancer of the greenhouse effect. According to Thorpe (2009), the digestive process is responsible for ~600 Tg of CH₄ annually in the atmosphere. This value represents, unsatisfactorily, a large slice of ~55% to 70% of all CH₄ gas emitted annually into the atmosphere.

Overall, the worldwide global demand for meat is growing, but at different rates in different regions. The worldwide beef, pork, and poultry production in 2012 was 63.3, 109.1, and 105.6 million tons (FAOSTAT, 2016). In Europe and in the United States, the biggest meat producers in the 20th century, consumption is growing slowly. On the other hand, in the fast-growing economies in Asia, such as China and India, an 80% increase in the meat sector is expected by 2022 (HBF-FEE, 2014).

The increase in food production, especially regarding the increasing sources of highly protein foods to meet the future demand of the population, is faced by certain challenges (Singh-Ackbarali & Maharaj, 2017):

- There is not enough land for the expansion of livestock.
- If predatory ocean fishing continues, this activity may deplete resources for future populations.
- The high cost of feeding animals puts in debate if that food should be used for animals rather than being used for feeding starving population around the world.
- Increased competition for water resources.

The production process of different types of meat is identical, except for poultry. The production process of the latter product has some different stages.

The meat production process is composed of two fundamental processes: slaughter and processing. The preparation process of raw meat and meat products (from slaughter to storage and conservation in cold) requires several external resources, such as water, thermal, and electrical energy. The storage and/or transport of meat or its derivatives also involve the consumption of large quantities of energy. The cold storage is used to ensure the maintenance of the organoleptic properties. Thus, the entire process of production of meat and meat products involves the use of large amounts of energy (Silva et al., 2016).

The production of meat products as sausages and ham is mainly industrial, although based on traditional processes. Changes introduced in the traditional process mainly involve the mechanization and the use of drying and/or smoking mechanisms under temperature and humidity control. This technological evolution enabled a continuous production throughout the year, without the influence of climatic conditions.

Refrigeration systems are indispensable within the production processes of meat industry to prevent changes in meat composition, bacteria action, and development of microorganisms and to obtain the stabilization and the organoleptic characteristics of the products (Savell & Mueller, 2005). The consumption of electricity for refrigeration systems in these industries are 60%–90% in slaughterhouses (EC, 2003; Marlow & Colley, 2007) and 40%–50% in meat processing industries (Ramírez et al., 2006a,b,c; Alcázar-Ortega et al., 2012). Electricity costs may correspond to two-thirds of the total energy costs in meat processing industries (HTC, 2009).

The typical process of meat slaughter, except poultry, comprises essentially the following operations: reception, antemortem inspection, animal's slaughter, carcasses and offal cleaning, postmortem inspection, cooling, cutting, processing, and dispatch. For each animal species, there is a specific circuit where carcasses are moved through fast cooling tunnels and refrigeration or freezing chambers.

Rapid cooling is one of the most used methods (Bowater, 2001). First, it consists in rapidly lowering the initial temperature of the postmortem carcasses from 38–40°C to 15–20°C. Afterwards, the meat temperature needs to be stable on a value below 7°C. To achieve this temperature in the inner center of the meat, it must be placed in a rapid cooling tunnel or in a cold room with strong air circulation. The air temperature and relative air humidity must

be around -1°C to 2°C and 82% to 90%, during ~ 4 h for bovine carcasses and 2 h for porcine and ovine carcasses. Following, the carcasses must be placed inside cold storage chambers with low air circulation. In case of freezing the meat, the temperature and relative humidity values must be -28°C to -40°C and 85% to 95%, respectively.

There is a great diversity of traditional sausages, produced with different raw materials and ingredients, but they all have a similar production process. The manufacturing process of sausages is composed of several operations. Cutting, mixing, and filling operations are held in air-conditioned rooms with a 12°C maximum temperature. During the maturation operation, the mixture of meats with condiments is kept in cold storage chambers, with temperatures between 1°C and 6°C and a relative humidity of 80%–85%, from 24 to 48 h. The drying process of sausages is accomplished by controlled atmosphere or through smoke drying. The operation time varies according to the size of the sausages. Typically, between 5 and 15 days for thin products and 30–60 days for thicker products (Arнау et al., 2007). The drying process with smoke requires exposing the sausages during 3–5 days to the action of heat and smoke resulting from combustion of wood.

Ham is a product obtained artificially in cold rooms from the aging of the hind legs of white pigs during an approximate period of 6 months. The production process consists of a set of operations with different values of temperature, relative humidity, and air circulation. The main stages of the production process include salting, postsalting, drying, and stuffing. Salting is intended to provide the proper amount of salt to the legs, keeping them involved in salt from 8 to 12 days. This phase takes place inside the cold storage chambers with high humidity and low temperature (Arнау et al., 2007). In the postsalting phase, the salt diffusion toward the inner part of the leg takes place from 30 to 45 days, considering the low air temperature and high humidity (6°C and 85% relative humidity). Following, the leg dehydration takes place slowly during a period of ~ 45 days. The temperature is gradually increased to 14°C while the relative humidity is lowered slowly to 75%. The stuffing operation ensures the specific organoleptic characteristics of the ham. It requires a minimum period of 15 days. The temperature is gradually increased to a maximum of 26°C and the relative humidity is kept close to 75%. After being manufactured, the hams are kept inside cold storage chambers for final stabilization during a minimum period of 15 days.

Livestock is an industry that generates a lot of income. Therefore, there is worldwide interest in this particular sector.

Nevertheless, due to the increased environmental impact of this sector, there is a need to develop new strategies and products to overcome its negative effects without putting at risk the food chain. On the other hand, a report from [Van Huis et al. \(2013\)](#) recommended the use of insects for human and animal consumption as a viable and sustainable source of protein. Entomophagy, or species of edible insects for food and feed, is an informal and widespread feeding practice for ~80% of the world's population. Insects are part of the traditional diets of at least 2 billion people according to [Van Huis et al. \(2013\)](#).

According to [Singh-Ackbarali and Maharaj \(2017\)](#), the market in general and the potential consumers will have to be convinced to accept edible insects and food products with insect ingredients as tasty, viable, and safe for consumption. Masking the shape of the insect can be a good strategy. An example is the use of insect powder in protein bars. Including insect ingredients on test dishes in popular restaurants can also promote acceptance among the population and offer opportunities for more adventurous chefs to develop new recipes using the delicacy. The market increase will drive a greater volume of business to the insect farms and this will help the insect farmers to overcome the market challenge and boost the expansion.

Searching for cleaner production alternatives or changing our customs and paradigms about food becomes necessary to meet the population's future food demands. It is evident the need for change in the sector of livestock production whether by adding new and cleaner products such as the above-mentioned example encouraging the insects' consumption that has a more sustainable ecological footprint. If the livestock sector remains focused on animal creation, it will be unable to attend the world population needs for food in the near future.

Price inflation of livestock products should also be discussed. The livestock production is still very much dependent on manual labor. The increasing demand for products of animal origin can increase its market price and making it difficult to achieve a healthy diet with a good amount of protein for the low-income population.

4 Dairy Sector

The dairy sector is one of the livestock subsectors of greater importance. Products such as milk, cheese, and yogurts are consumed worldwide and are of paramount importance for people's food base. In addition, some of these products have an added

value due to ancient and artisan processes used in their manufacture. Cow's milk is the most produced and consumed worldwide, but also the milk of other mammals is used for consumption such as milk of sheep, buffalo, and goat. Dairy products are an important source of protein and calcium, playing an important role in nourishing the gastronomic levels.

The consumption of dairy products is significant in areas of the world such as Europe and the United States. In turn, in high-density populated areas such as China, there is a low per-capita consumption of such products (Silva et al., 2016). The dairy industry employs thousands of people around the world, from livestock to distribution. This industry branch is currently highly advanced in terms of technology, consisting of fully automated processes focusing on improved food safety. See an example of a dairy plant in Fig. 7. Before reaching the consumer, the milk is subject to thermal processes such as pasteurization or ultra-pasteurization to ensure its food security. The milk suffers a heating process followed by a cooling process to ensure the destruction of potential harmful bacteria.

Cheese is a subproduct of milk widely consumed worldwide. It can be manufactured from the milk of various animals such as cow, sheep, or goat. It derives from the coagulation of milk, by separating milk into curd and whey. The whey is removed and the curd undergoes bacteriological processes leading to the production of cheese. The final characteristics of the cheese depend on the production method. There are hundreds of types of cheese throughout the world. More than half of world's cheese is produced in Europe. The three largest European cheese producers and consumers are Germany, France, and Italy.



Fig. 7 Dairy products plant.
From @Marcin Balcerzak/123RF.
com.

During the last four decades, milk production grew by 64%, reaching a value of 790 million tons in 2012. The cheese production is around 27% within this sector. In the last decade alone, the world cheese production increased by 32% (Mikkelsen, 2014). Predictions suggest that in 2020 the world production of cheese will reach up to 25 million tons. In the course of their activities, dairy companies use electrical energy to drive cooling systems, pumps, fans, compressed air systems, lighting, and one or more types of fuel to burn in combustion plants (boilers), for water heating or for steam production (cleaning operations or production processes). The increase of population in cities and the increase of food quality and safety standards turns the supply chain to be more energy demanding, especially on the refrigeration systems (Artés, 2004; Coulomb, 2008; James & James, 2010), which are major electrical energy consumers (Ramírez et al., 2006a,b,c; Gautherin et al., 2007; McFarland & Bivens, 2007; Tassou et al., 2010; Gaspar et al., 2014; Silva et al., 2014). Some authors highlight the possibility of assessing the energy performance of food industry, such as cheese making, using benchmark indicators as the specific energy consumption (Reindl et al., 2005; UNIDO, 2010; Xu & Flapper, 2010; Nunes et al., 2014a, 2015, 2016).

The manufacturing process of cheese from raw milk involves several steps that are similar in all traditional cheese industries. However, there are industries that carry out all steps using technology while others still perform some of the steps by hand, in particular, salting, pressing, and periodically washing the cheese. In general, the ripened cheese manufacturing has a duration of between 30 and 45 days. The main raw materials used for the cheese manufacture are sheep and goat milk. Some industries also manufacture fresh cheese (pasteurized milk without maturation and with a short life span) and cheese curd (resulting from whey heated to a temperature of 90–95°C, for 2–2.5 h, followed by filtration). The conservation of these two products is performed in cooling chambers at a temperature of 4–6°C and relative humidity of 85%–90%. The manufacturing process of these latter products requires more use of cold and heat, particularly, the use of refrigeration systems to cool down and preserve the milk and cheese products.

5 Horticultural Sector

Fruits and vegetables (horticultural products) are part of agricultural products. The horticultural products possess an active metabolic state even after the harvest, making them highly

perishable (Fraser, 1998; Álvaro, 2001; Filho, 2008). In addition of being the most consumed foods products, horticultural products are also widely used as raw materials in various food industries (wine, olive oil, juice, and frozen). The driving factor of the increase of the production of horticultural in the world is the growth of the world population.

Fruits form parts of horticultural products are settled in the human diet due to their nutritional context. The fruit production has been increasing with the years, following the growth of the world population. The largest worldwide production of fruits consists of bananas (100 million tons), watermelons (99 million tons), apples (71 million tons), and grapes (68 million tons). On the other hand, fresh vegetables (249 million tons) and tomatoes (154 million tons) are the most produced vegetables in the world. The production of vegetables increased worldwide between 2009 and 2012. In 2009, the fresh vegetables represented 24.4% of horticultural products produced worldwide. The largest vegetable producers are Asian countries, particularly China, Japan, and India. The per-capita consumption varies from region to region of the world due to the eating habits and living standards of each country. At the World level and European level, the highest per-capita consumption occurs in the sector of cereals, followed by vegetables and fruits.

Most of the horticultural products are produced seasonally and they are highly perishable. Thus, its shelf life is very short. Additionally, harsh handling of horticultural products promotes their mechanical damage, stimulates weight loss, and increases exposure to the attack of microorganisms. Exposure of horticultural products to a fast reduction of vapor pressure, the use of low relative humidities and unnecessary air currents are harmful to the quality of products (López & Rodríguez, 2000). Refrigeration with controlled atmosphere is used to minimize the above effects and extend the shelf life of horticultural products (Parikh et al., 1990). According to López and Rodríguez (2000), Marvillet (2001), and Rosset et al. (2002), a fast temperature decrease of the horticultural products avoids many of the aforementioned problems associated with the postharvest period. The immediate application of cold allows reducing the loss of vitamins and sugars, organic acids, water as well as the speed of biochemical and enzymatic reactions (IIF, 2008). The best conservation temperature range for most of the fruits is 0–4°C. The ideal temperature range for the conservation of vegetables is 3–6°C (López & Rodríguez, 2000; Álvaro, 2001).

Given the relevance of rapid cooling to remove the heat of harvest, several technologies have been developed for these

applications in the last years, such as cooling chambers with variable-speed fan evaporators, cooling tunnels with water, vacuum and immersion, or spraying techniques with ice water ([Marvillet, 2001](#); [IIF, 2008](#)).

6 Food Processing Industry

The main aim of the agrifood industry is to provide consumers and society with a range of safe, healthy, nutritionally rich, economically accessible, and sustainable food products, while maintaining their competitive capacity. Typically, the agrifood industries are processing plants, which have specific characteristics, namely the use of limited resources with a high level of perishability, and therefore their use should be as efficient as possible. In general, this industry transforms agricultural products, not only for the production of foodstuffs for humankind, but also for animals, given their indirect importance in the human food chain. Owing to its positioning between agriculture and the markets for consumer products, the agrifood industry has its own characteristics, which makes its development sensitive to the behavior of raw materials and to the organization of markets. In fact, in the majority of cases, it works with raw materials, which begin to deteriorate soon after collection. In addition, the specific characteristics of certain products, such as vegetables, fruits, and dairy products, and their seasonality must be taken into account. The evolution of consumption habits and distribution circuits, the increasing segmentation of markets, the multiplicity of products marketed, and the economic constraints imposed by competition have led agrifood industries to develop their own strategies and production tools. Nowadays, there is a great development of specialized methods in the manufacture of food products, with the conservation and processing of raw materials, with widespread application of refrigeration, freezing, and dehydration ([Wang, 2008](#)).

The agrifood industry is part of the manufacturing sector. At the European level, it is one of the largest sectors, with a very significant weight in the economy. In fact, the agrifood industry was the leader in the European Union's employment sector, with 28,900 companies and 4.25 million jobs, and had a turnover of 1089 billion euros ([FoodDrinkEurope, 2016](#)). The role of small- and medium-sized enterprises (SMEs) is very significant, with 49.5% of total turnover and 62.8% of total employment. Exports of food products to countries outside the European Union amounted to 98.1 billion euros, equivalent to 17.8% of global exports ([FoodDrinkEurope, 2016](#)).

Refrigeration systems are used throughout the production process to preserve the physical and chemical characteristics of products, prolonging their life span. The main aim is to obtain environmental conditions, in terms of temperature and, where appropriate, relative humidity, that prevent the development of microorganisms, which may deteriorate the products. Refrigeration systems are also used in the processes of rapid freezing, rapid cooling, and dehydration of products. Some products, such as fruits and vegetables, meat or milk, for effective preservation, require a rapid decrease in their temperature, and cooling systems must be used to promote rapid cooling. In the production processes of dehydration/hydration it is intended to control water activity in food products, making them more stable at room temperature (Arnau et al., 2007). For these processes, systems are required to control the temperature and the relative humidity of the air, generally using air treatment units, such as air-to-air heat pumps. Typically, these systems are used in the processes of manufacturing sausages, hams, and cheeses. The great diversity of functions of the refrigeration systems used in the agrifood industries means that the associated energy consumption is strongly dependent on their characteristics and operating conditions. When just only the ambient temperature of the cold chambers is to be maintained, the energy consumption will be lower than in specific cases, where a rapid decrease in ambient temperature is required. In systems for maintaining ambient temperature inside the refrigeration chambers, it is necessary to withdraw the amount of heat relative to the thermal loads generated therein, namely those related to heat transfer on the chamber walls, air infiltrations, lighting, machines, people movement, and the products themselves. From the foregoing, it becomes clear that an intensive and widespread use of refrigeration systems in agrifood industry is essential, which results in a high consumption of energy. Therefore, the search for greater sustainability in the agrifood industry requires the introduction of technologies that are less energy intensive and environmentally demanding. In fact, energy consumption of refrigeration systems in food industries has increased due to increased food manufacturing and requirements imposed by quality, hygiene, and food safety standards (Ramírez et al., 2006a,b,c). Due to the high level of utilization, in many industrial processes, refrigeration systems are considered energy intensive (Xu et al., 2009; Xu & Flapper, 2010; Nouri et al., 2013). Due to the characteristics of the agrifood industry, which is composed of a large number of small food processing industries, the group also contributes to the high consumption of electricity in various countries (Ramírez et al., 2006a,b,c). As an example, in

2008, in the EU-27, the majority (99.8%) of the industries present in the economy were SMEs—approximately 20.9 million—and more than nine companies out of ten (92%) were classified as microenterprises employing <10 workers. This scenario is most relevant in Southern European member states, such as Italy, Spain, and Portugal (Eurostat, 2016). In some sectors, energy consumption increased considerably as a result of increased activities and use of refrigeration systems (Ramírez et al., 2006a). These systems consume large amounts of electrical energy, contributing significantly to the operating costs of the industries with significant cooling needs. For these industries, refrigeration systems can account for around 85% of global energy consumption (Victoria, 2009).

In the United Kingdom, 11% of the final energy was consumed by the food industry and some sectors used more than 90% of electrical energy with cooling systems (Swain et al., 2009). Many economic sectors need to remove the initial thermal load from the products, often by rapidly cooling the products. Swain et al. (2009) points out that in the United Kingdom there are six categories where it is necessary to withdraw this energy: milk (532 GWh/year), meat (114 GWh/year), potatoes (154 GWh/year), other vegetables (36 GWh/year), fish (6.5 GWh/year), and fruits (5.9 GWh/year). Furthermore, using the best technologies for cooling available in the United Kingdom, annual energy savings of 59 GWh in potato cooling, 128 GWh in cooling milk, and 51–80 GWh in cooling of the carcasses can be achieved. Burfoot et al. (2004) have found that 18% of the annual energy consumption of United Kingdom refrigerated food sector is used in industries to maintain low temperatures to prevent the growth of microorganisms in food. In France, industrial refrigeration accounted for 4% of electricity consumption and almost 7% of electricity consumption. It was estimated that electric energy consumption in the dairy sector was ~2.9 TWh, and of this quantity, 26% was exclusively consumed by cooling systems (Gautherin et al., 2007). In terms of electricity consumption, the dairy sector occupied the fourth position, following the large food distribution (3.6 TWh), the cold storage (2.45 TWh), and the local business (1.4 TWh). This consumption was above the consumption of electricity in other food activities, such as cattle slaughterhouses (370 GWh), charcuteries (369 GWh), and breweries (203 GWh) (Gautherin et al., 2007). According to these authors, the electricity consumption for liquid milk production, butter production, cheese production, and other dairy products corresponded to 1, 0.18, 1.2, and 0.56 TWh, respectively. In particular, the energy consumption related with the use of refrigeration systems in each of these sectors was 34%, 6%, 41%, and 19%, respectively. Dairy establishments, particularly in

the manufacture of cheese and meat processing, are particularly energy intensive because they need it both for refrigeration and for heating. For example, [Ramírez et al. \(2006b\)](#) point out that in the Netherlands dairy production and the production, processing, and conservation of meat account for about 15% and 9% of the total energy consumed in the food sector, respectively.

The amount and the type of energy used vary greatly depending on the type of products manufactured. For the Australian dairy industries, particularly for the manufacture of cheese, the use of electric and thermal energy is in the order of 27% and 73% of total energy, respectively, while in the manufacture of milk for human consumption these values are around 66% and 34%, respectively ([Prasad et al., 2004](#)). Industries that mainly produce milk for consumption and cheese use energy for heating, milk pasteurization, refrigeration and cooling, lighting, compressed air, air conditioning, pumping and processing equipment, and auxiliary operations. Industries that manufacture concentrated milk products and certain types of powdered cheese require additional thermal energy to perform agitation, separation, concentration, evaporation, and drying operations.

In view of the high-energy consumption, food-processing establishments are now in a position to analyze and take care of them by implementing measures and actions that promote good energy use. Energy efficiency can offer a range of savings across a number of domains such as reducing energy costs, reducing maintenance costs and confidence in the system, improving safety, increasing productivity, better cooling load adequacy and equipment capacity, better working environment and reduction of resource consumption, and greenhouse gas emissions ([Victoria, 2009](#)). The value of energy savings in cooling systems is related to the number and type of measures applied and the quality of the technology used. A simple improvement in operational practices or good construction of the plant with a minimum of expenditure can often lead to a reduction in energy consumption of up to 15% or even more, while using the best techniques of the cooling system elements can lead to a potential energy consumption reduction of between 15% and 40% ([Manske et al., 2001](#); [Victoria, 2009](#); [Guilpart, 2010](#)). According to [Victoria \(2009\)](#) the improvement of energy efficiency in the existing systems can be achieved by means of an action plan that involves the following steps:

- (i) analysis of the required cooling capacity,
- (ii) analysis of the quality of the thermal insulation used,
- (iii) evaluation of the distribution of the refrigerant in the system,
- (iv) evaluation of system control systems and heat rejection processes,

- (v) optimize maintenance and finally,
- (vi) to evaluate the improvement of the system after the intervention.

Landymore (2012) also points out that there have already been significant improvements in refrigeration technology in the refrigeration sector, but some of the solutions are difficult to implement by small- and medium-sized establishments because they are very costly. In refrigeration and air conditioning systems, the compressor is the largest consumer of electricity, and in most cases, it consumes about 70% of the total electricity. One of the ways to combat the consumption of electricity is to shorten its operating time. In the dairy sector, a set of energy-efficiency measures are being implemented in both terms of the refrigeration facilities themselves and production processes and manufacturing (Gautherin et al., 2007). These measures include lowering the condensing temperature, increasing the evaporation temperature, using variable speed drives, using advanced control of refrigeration plants, resizing pasteurizers, assessing energy savings, the estimation of the number of equipment used in the processes, and the associated energy consumption. The estimated energy gains in relation to the initial consumption values are between 10% and 20%. According to Mirade et al. (2012) the precise analysis of the consumption of energy in the cheese manufacturing industry allows to highlight four main areas of energy consumption, two of them corresponding to the consumption of electricity and the other two to thermal energy. Pumps, fans, conveyor motors, lighting systems (35%), refrigeration systems, and milk storage equipment (20%) are the electricity consumers in dairy industries. Thermal energy is consumed by heating systems, evaporators and dryers (40%), and equipment used in the daily cleaning process (5%). Overall, large energy savings can be achieved in food industry if efficient management systems and energy consumption monitoring policies are implemented (Fritzon & Berntsson, 2006; Muller et al., 2007; AlQdah, 2010) and if existing technologies and conventional systems are targeted for maintenance tasks (IIR, 1982; Gigiel & Collett, 1989; James & James, 2010). Energy savings can also be achieved if current systems are improved, such as using high-efficiency electric motors (EC, 2006; Worrell et al., 2009) or implementing variable speed systems in the engines (Tassou & Qureshi, 1998; Abdelaziz et al., 2011). Finally, it can be by the development of new food conservation technologies with a very low potential for environmental impact together with the reduction of food waste (Lung et al., 2006; Pereira & Vicente, 2010; Tassou et al., 2011; James & James, 2011).

7 Recent Developments and Future Scenarios

The goal of FAO in the coming years focuses on sustainable consumption and sustainable production. According to FAO, it is vital to ensure sufficient, accessible, nutritious production and consumption, maintaining the natural resources and ecosystems of which they are part. Agricultural production chains play a central role in all societies and are fundamental to ensuring sustainable development.

Sustainable food systems are key points to address food security, poverty alleviation, and adequate nutrition, and play an important role in building a society able to recover the balance between environmental and production costs.

However, our agricultural production system is under strong pressure to answer to increasing demand, climate, and soil changes, mostly due to human interference itself. Some noteworthy projections that highlight the need for sustainable food systems are the following:

- Demand: It is estimated that by 2050 the world population will be 9 billion. Today, we are 7.2 billion;
- Waste: Today, we waste around 30% of the total food produced;
- Hunger: 12.9% of the population in developing countries suffer from chronic hunger;
- Obesity: About 30% of the world's adults suffer from obesity;
- Prices: People in the poorest areas spend 50%–80% of their income on food, so they are extremely vulnerable to price rise;
- Climate change: Agricultural production is a natural resource, so it is extremely vulnerable to climate change on the planet;
- World productive system: Agricultural production itself is a major cause of environmental impacts. It is estimated that 70% of the waters, large part of deforestation, and biodiversity loss was caused by agricultural production.

Finding ways to produce food without adding more inputs, not increasing the area of agricultural production through deforestation, reducing the waste in production, and bringing the countryside closer to cities, thus avoiding transport waste and reducing emissions with transport, are the challenges that all agricultural sectors must overcome in the coming years. One of the strategies is related to the promotion of the concept of sustainable cities. According to [Peter and Swilling \(2012\)](#), the implementation of food resilience with the boost of local production and consumption, encouraging agricultural production activities in the cities and their surroundings, may contribute to mitigate the effects of global climate change.

The effects of a major global environmental impact can make vulnerable the food supply to cities. The encouragement of the use and local production of organic products are measures that reduce the carbon footprint in food and transportation. With the purchase of local products, it is predicted the reduction of green gases emissions due to burning of fossil fuels, intermediates, and food waste, mainly of horticultural products, since they are products more sensitive to transport and storage.

Another facet that may contribute to reduce the environmental impact caused by food systems is related to the need of a refrigeration system to maintain the organoleptic characteristics of food products. All types of coolant fluids used in refrigeration applications have a negative impact on the environment.

First, the hydrochlorofluorocarbons (HCFCs) were phased out due to their high ozone depletion potential (ODP). HFCs originally replaced the HCFCs. However, HFCs are also a significant contributor to global warming. Thus, countries such as the EU and the United States began to phase out their use independently. In October 2016, the Kigali Accord signed by more than 170 countries aims to counter further climate change by cutting the worldwide use of HFCs. If the application of this accord is successful, it will result in the reduction of the equivalent of 70 billion tons of carbon dioxide between 2020 and 2050. Thus, this accord marks a significant milestone in the development of the global HVAC/R industry because this type of refrigerant is used extensively. In the near future, equipment manufacturers must start developing equipment for a world where also HFCs are banned. Contributing to this end, extensive tests on the use of hydrocarbons (HCs) and hydrofluoroolefins (HFOs) have been performed by academia and industry. Some of these refrigerants will only grow in importance as real alternatives to the actual state of the art. It must be pointed out that while some newer refrigeration equipment can be retrofitted to use alternative refrigerants, the older ones have to be replaced because retrofitting is not cost effective. It is important to highlight that short-term investment required to replace older refrigeration equipment can be diluted during the years of operation due to the increased efficiency and reduced operating and maintenance costs.

The technology based on the thermodynamic vapor compression cycle is widely used in industrial, commercial, and domestic refrigeration systems. It is a technology with proven merits and accepted by many different sectors. It continues to be a constantly evolving technology, by the technological enhancement of the various components of the system (compressor, evaporator, expansion valves, and condenser) and its accessories. These advances include the application of new materials, new coolant

fluids with greater heat exchange capacity and reduced environmental impact, technological solutions and innovative designs and the precise control, regulation, and command of the refrigeration system. This latter technological advance may lie in the adoption of a multiplicity of sensors for direct or indirect monitoring of numerous parameters, actuators with operation regulation, and the use of microcontrolled systems with algorithms that may use intelligent control techniques. However, depending on the specificity of the industrial process, there is a need to develop further the refrigeration system and its components, both by considering innovative solutions at the level of the system components and of control, regulation, and command that enable the processing of food products with the required nutritional and organoleptic characteristics.

On the other hand, the current demand for healthier products with superior organoleptic quality and that have specific health and well-being properties (such as functional foods or bioactive properties) has grown exponentially. These trends added to the need of ensuring the microbiological safety and the extension of shelf life promoted the development of new and emerging alternative technologies for food processing. The competition with emerging economies allows delivering products to the market at increasingly competitive prices, forcing the agrifood industry to compete through innovation and creation of value-added products.

The thermal processing includes a set of unit operations such as bleaching, pasteurization, and sterilization, based on external heat generation and its transfer by conduction, convection, and radiation mechanisms. To avoid compromising the microbiological safety, all these operations end up affecting the quality parameters, reducing nutritional value, and causing changes in organoleptic properties, namely flavor, texture, color, and aroma.

To overcome the limitations of traditional methods of pasteurization and sterilization, it is increasingly necessary the strict control of the applied heat treatment and of other processing/nonheat technologies to ensure food safety with the highest quality. In this context, the development and implementation of emerging and innovative food processing technologies that aim, besides overcoming the limitations of food quality, to increase efficiency and production rates are required.

Beyond the traditional food preservation methods of thermal processing, freezing, salting, and drying, new methods of processing and packaging continue to emerge. These methods can extend the shelf life and freshness of perishable foods. A brief description and some possible future applications for each of these technologies are given in [Tables 1](#) and [2](#). [Table 1](#) includes

Table 1 Description of the Emerging Nonthermal Technologies and Their Future Applications

Technology Type	Process	Applications and Trends	Advantages and Limitations
High hydrostatic pressure (HHP)	High-pressure processing is carried out with intense pressure in the range of 100–1000 MPa, with or without heat, allowing most foods to be preserved with minimal effect on taste, texture, or nutritional characteristics	It has been applied to shellfish, sliced meats, vegetables, cheese, meat, fish, juices, and smoothies, ready to eat meals, sauces, and salsas successfully. Several rice-based foods are available with novel textures induced by high-pressure treatment. Commercial products have now been appearing in the United States and Europe	The main advantage of high-pressure processing compared with thermal sterilization and pasteurization is maintenance of sensory and nutritional characteristics of treated food products. The limited effect of HPP (at moderate temperature) on covalent bonds provides a minimal effect on food chemistry. HPP provides a means for retaining the food quality while avoiding the need for excessive thermal treatments or chemical preservation
Pulsed electric fields (PEF)	PEF processing involves treating foods placed between electrodes by high-voltage pulses in the order of 20–80 kV (usually for a couple of microseconds). The applied high-voltage results in an electric field that causes microbial inactivation	PEF is restricted to food products without air bubbles and with low electrical conductivity. In the treatment of products with PEF we find skimmed milk and fruit juices. This technology has also been applied for pasteurization of foods such as juices, milk, yogurt, soups, and liquid eggs	The advantages of this technology are an ongoing process: obtaining quality fresh produce; nutrient retention in products; application for acidic foods. This technology spends less treatment time, withstands low temperature during treatment, replaces conventional heat pasteurization, extend shelf life, and maintain food safety with low processing costs. Disadvantages include the high cost of capital, not suitable for solid food, and restricted to food products without air bubbles and with low electrical conductivity
High-intensity light pulses	The pulsed light processing can be described as a sterilization or decontamination technique used mainly	Liquid foods (cold pasteurization of liquid food such as milk and juices) and solid foods (fruits, vegetables, eggs, shellfish, and meat).	The advantages are the intensity of light that lasts for only a second, is 20,000 times brighter than sunlight, but there is no thermal effect, so quality and nutrient content are retained. As a disadvantage of the process, a possible food

Table 1 Description of the Emerging Nonthermal Technologies and Their Future Applications—Cont'd

Technology Type	Process	Applications and Trends	Advantages and Limitations
	to inactivate surface microorganisms on foods, packaging material, and equipment. This technique uses light energy in concentrated form (up to 70 kV/cm) and exposes the substrate to intense short bursts of light	Future surface treatment of foods and package material decontamination applications are anticipated using pulsed light technology	preservation problem arises because the folds or cracks in the food may protect the microbes from being exposed to pulsed light
Membrane technology	Reverse osmosis (RO) uses a pressure gradient across a semipermeable membrane to squeeze water through membrane. Ultrafiltration (UF) uses much a lower pressure of 1–10 bars and much more open membranes, which pass salts, sugars, and organics into the molecular range typically from 5000 to 1,00,000 depending on the membrane type	The primary goal of UF in fruit industry is to replace the holding filtration and decantation steps of traditional process. Both RO and UF have promising uses in fruit and vegetable juice industry as a unit operation for concentration or aroma recovery and clarification of juices, respectively	UF system generates cost savings and work force reduction; process control is simple; no cooling water equipment is needed and products have better flavor. RO is a well-established process for concentration/preconcentration of raw and clear depectinized juice from fruits and vegetables. It consumes 10 times less energy for renouncing water when compared with conventional evaporators
Irradiation	A process where food is exposed to ionizing energy, utilizing gamma photons emitted by 60 Cs (or much infrequently by 137 Cs) radioisotopes, machine-generated X-rays of max. 5 MeV, or,	Food irradiation is effective against a wide variety of pathogens such as bacteria, fungi, viruses, and parasites. Main applications are inhibition of sprouting, insect disinfestation, parasite disinfestation,	The process of food irradiation is used throughout the world to reduce the risk of illnesses and food poisoning. In addition to some safety concerns, irradiated food has other disadvantages, such as poorer taste and nutrient content. Irradiated food can be more expensive, due to the upfront costs of a food irradiation facility. Irradiation cannot

Continued

Table 1 Description of the Emerging Nonthermal Technologies and Their Future Applications—Cont'd

Technology Type	Process	Applications and Trends	Advantages and Limitations
Food preservation with ozone	accelerated electrons of max. 10 MeV kinetic energy	shelf-life extension (radurization), and elimination of nonspore forming pathogenic bacteria (radicidation)	eliminate pesticides and other chemicals in food, nor can irradiated food be handled and packed in unsanitary conditions without contamination recurring
	Ozone is a safe, powerful disinfectant, and it can be used to control biological growth of unwanted organisms in products and equipment used in the food processing industries	In aqueous solutions, ozone can be used to disinfect equipment, process water, and some foodstuff. In gaseous form, ozone can act as a preservative for certain food products and can also sanitize food-packaging materials. Some products currently being preserved with ozone include eggs, fresh fruits and vegetables, and fresh fish	As main advantages, it stands out that ozone is a powerful oxidizer available, instantly destroys microbes, eliminates chemical storage, environmentally friendly; stops mold spores, does not affect product taste, and no harmful by-products and can be used in air and water
Modified and controlled atmosphere storage	Controlled atmosphere (CA) is the alteration of the natural gaseous environment (usually O ₂ and CO ₂ levels) and maintenance of this atmosphere at prespecified conditions throughout the storage time. Modified atmosphere (MA) is the initial alteration of the gaseous environment in the immediate vicinity of stored and packaged product	CA and MA are mainly used on fruits and vegetables. The CA- and MA-based technologies are expected to go on contributing to meet the increasingly rising quality standards demanded by the fresh food market	CA storage is normally preferred for long-term storage of large quantities of single commodities, mostly apples and pears, although an ever-increasing variety of crops (e.g., banana, cabbage, and kiwifruit) have also been tested with success. CA storage is claimed to be expensive because of the initial capital investment on equipment, coupled with the sustained energy requirement needed to maintain the storage conditions at preset values

Table 2 Description of Emerging Thermal Technologies and Their Future Applications

Technology Type	Process	Applications and Trends	Advantages and Disadvantages
Ohmic heating	An AC current is passed through a food sample, which leads to generate internal energy in foods. As a result, an inside out heating pattern is generated. The heat generated destroys microorganisms in a manner similar to classical thermal processing. Ohmic heating is distinguished from other electrical heating methods either by the presence of electrodes contacting the food, frequency, and waveform	Ohmic processing has the potential to impinge on the frozen foods market because its product has the taste, texture, color, and vitamins of fresh, homemade food	The advantage of this technique is that it uniformly heats food with different densities. It saves significant time energy in hot air and freeze drying of foods and enhances extraction yields of some processing operations. Another advantage is its ability to heat materials rapidly and uniformly, including products containing particulates. The system instantly and evenly heats liquids and solids. With ohmic processing, the sterilization process takes place at very high temperatures, very quickly and therefore a high-quality product is obtained
Infrared (IR) heating	Infrared (IR) heating technology consists of exposing an object to IR radiation (wavelength from 0.78 to 1000 μm), with the energy generated being absorbed by food products	IR has been applied in drying, baking, roasting, blanching, pasteurization, and sterilization of food products. Scaling up and commercialization of the IR-based technologies are expected to open new avenues to deliver desirable foods to consumers that have a reduced footprint regarding the consumption of natural resources and provide significant socioeconomic benefits to the society	IR provides significant advantages over conventional heating, such as reduced heating time, uniform heating, reduced quality losses, absence of solute migration in food material, versatile, simple, and compact equipment, and significant energy saving. Combinations of IR heating with MW heating and other common conductive and convective modes of heating have been gaining momentum because of increased energy throughput

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Table 2 Description of Emerging Thermal Technologies and Their Future Applications—Cont'd

Technology Type	Process	Applications and Trends	Advantages and Disadvantages
Microwave (MW) heating	A wave is propagated and reflected according to the laws of physics in the frequency range from 300 MHz to 300 GHz. MW works well with smaller quantities of product with a dipolar nature	The industrial MW processing applications currently in use can be summarized as dehydration of low moisture solids, precooking of meat products, pasta drying, and tempering of frozen products. The recent MW heating applications in the food industry may be listed as MW baking, drying, frying, thawing and tempering, pasteurization and sterilization, roasting, blanching, and extraction	MW processing delivers a more homogeneous heat treatment at a faster rate than the conventional method of heating. MWs are endowed with some special characteristics such as high penetrating quality which results in the uniform heating of materials, selective absorption of radiation by liquid water and capacity for easy control. These impart some unique effects to the dehydrated material such as improved quality and good texture
Radio frequency (RF) heating	An RF generator creates an alternating electric field between two electrodes. The material to be heated is placed between the electrodes, where the alternating energy causes polarization, wherein which the molecules in the material continuously reorient themselves to face opposite poles. RF technology uses electromagnetic radiation in the frequency range from 300 kHz to 300 MHz. RF works well with large quantities of material with high ionic conductivity	Some of the known applications of the RF heating system are bakery products and comminuted meat products. Other potential applications include reduction of Salmonella in eggs and destroying harmful bacteria in fresh fruit juices. The potential of RF is greater when used in hybrid systems that take the volumetric heating advantages of dielectric heating and couple them with conventional processing for efficient, rapid, and high-quality results	RF overcomes many heat transfer problems as water is preferentially heated and provides a considerable decrease in processing time. It acts as a moisture leveling process and it has good overall energy efficiency. The RF equipment has high initial capital cost and it is subject to fluctuations in the price of electricity. Skilled labor is required for the tuning and all generators and applicators must be properly shielded and specially designed to meet product-specific requirements

nonthermal technologies such as high hydrostatic pressure (HHP) (Medina-Meza et al., 2014; Hsiao-Wen et al., 2017), pulsed electric fields (PEF) (Cacace & Palmiere, 2014), high-intensity light pulses (Cacace & Palmiere, 2014), membrane technology (Cacace & Palmiere, 2014), irradiation (Albert, 2008; Odueke et al., 2016), food preservation with ozone (Cacace & Palmiere, 2014), and modified and controlled atmosphere storage (Fonseca & Malcata, 2003). Table 2 includes the description of the thermal technologies such as ohmic heating (Ahmed & Ramaswamy, 2007), infrared (IR) heating (Krishnamurthy et al., 2008), microwave (MW) heating (Ahmed & Ramaswamy, 2007; Tewari, 2007), and radio frequency (RF) heating (Fu, 2004; Tewari, 2007).

There are some other new nonthermal food technologies under development such as cold plasma, electrolyzed water, and thermosonication.

Cold Plasma: A second surface technology is cold plasma. Plasma is a high-energy gas that is created when an electrical current is passed through a gas. A well-known application of this principle is in fluorescent lighting. Until recently, plasmas could only be created at relatively high temperatures in a vacuum and the use of plasma in the agrifood sector and the packaging industry was therefore impractical. In the last few years, technological breakthroughs have made it possible to produce cold plasma under atmospheric conditions. Thus, it is now possible to apply the plasma technology in the food industry. Noble gases are used when radical formation is unwanted while oxygen is used for the production of ozone in the plasma. Depending on the used gases, temperature, activity, and stability of the plasma can be varied. No commercial equipment is available now. Low-temperature, atmospheric pressure plasmas have been shown to possess very effective germicidal characteristics. Their relatively simple and inexpensive designs, as well as their nontoxic nature, give them the potential to replace conventional sterilization methods in the near future.

Thermosonication: The combination of ultrasound and heat at moderate temperatures can cause enhanced inactivation of microorganisms. This may be particularly useful for pasteurization of certain beverages where a reduced temperature is desirable. Ultrasound has potential application for emulsified foods, especially where a product's rheological qualities can be improved by ultrasound treatment.

Electrolyzed Water (EW) is gaining popularity as a sanitizer in the food industries of many countries. It has been regarded as a new sanitizer in recent years. Production of EW needs only water and salt (sodium chloride). EW is produced by passing a diluted

salt solution through an electrolytic cell, within which the anode and cathode are separated by a membrane. By subjecting the electrodes to direct current voltages, negatively charged ions such as chloride and hydroxide in the diluted salt solution move to the anode to give up electrons and become oxygen gas, chlorine gas, hypochlorite ion, hypochlorous, and hydrochloric acid, while the positively charged ions such as hydrogen and sodium move to the cathode to take up electrons and become hydrogen gas and sodium hydroxide. EW has the following advantages over other traditional cleaning agents: effective disinfection, easy operation, relatively inexpensive, and environmentally friendly. The main advantage of EW is its safety. EW, which is also a strong acid, is different from hydrochloric acid or sulfuric acid in that it is not corrosive to skin, mucous membrane, or organic material. EW has been tested and used as a disinfectant in the food industry and other applications. Combination of EW and other measures is also possible to use to improve the process of disinfection of food.

In addition, joule heating and hydrostatic high pressure emerge at the forefront of the narrow range of technologies considered the most promising with these capabilities. Both technologies allow obtaining products with differentiating properties similar to those of a minimally processed product or even natural product in the case cold pasteurization (without heat input).

Joule heating consists in the principle that the electric current passing through the food allows the generation of internal energy, dissipated as heat. This technology is not dependent on heat transfer phenomena from an external source, allowing to reach levels of energy efficiency of around 90%. The main advantages of this technology are (Knirsch et al., 2010; Sastry et al., 2014) the following:

- ideal for the processing of viscous and particulate products, according to high-temperature short-time principle,
- precise control of heating rates, and
- low maintenance costs and easy coupling to existing thermal processing lines;

The operative mode of this technology is based on the dependency between time and temperature as in the widely established pasteurization and sterilization operations. However, the high investment and initial operating costs added to the lack of information and research on a large number of industrial processes have limited the applicability of the technology to the industrial level.

Hydrostatic high-pressure technology is a nonthermal method of preservation. It is presented as an alternative to conventional pasteurization. This process is performed at room temperature

or even at refrigeration temperature, ensuring better maintenance of the nutritional and organoleptic attributes of a fresh perishable product, resulting in the production of premium or gourmet quality products.

The main advantages of this technology are the following:

- nonthermal pasteurization;
- effect of processing independent of the size/geometry of the products, which makes the scale-up process unnecessary. Thus, the transition from a laboratory to industrial level is a simple process of adaptation, extremely fast and basically without inherent costs; and
- possibility to process liquids, solids, and mixtures thereof without the limitation of thermal processing, especially for solids.

Owing to its industrial development, hydrostatic high-pressure technology is nowadays, among emerging food conservation technologies, the technology with most commercial applications, being one of the most promising of the new applications and the fastest growing technology in the industry. This technology also allows for cold gelation of proteins and polysaccharides, with new properties as new textures, which can result in new organoleptic sensations, thus being very promising for the functionalization of ingredients.

Recently, hydrostatic high-pressure technology has proven to be very interesting for food sterilization when combined with temperature, in a process known as pressure-assisted thermal sterilization (PATS). This process allows the production of products without the need for refrigeration, but with better quality than the current sterilized ones due to the minor time and consequently lower thermal load. Ultrahigh-pressure homogenization is a technology that has also received attention. The main advantages of using high-pressure homogenization in emulsions include a narrow size distribution of particles, an aseptic processing, and the possibility of being used in highly concentrated as well as diluted formulations (Floury et al., 2004; Håkansson et al., 2009).

Until now, prospects of future scenarios cover new and emerging processing and conservation method of food products, but these are closely related with its energy consumption that also define the sustainability of the systems. The energy consumption resulting from the conversion process of fossil fuels in usable energy (electrical and thermal energy) release GHGs to the atmosphere. Thus, sustainability requires the reduction or rationalization of energy consumption (Garcia & Coelho, 2010). Agrifood industry shows continuous energy consumption by the cooling systems to ensure food safety, making this sector one of the largest

energy consumers. Several studies have been carried out to provide new tools, concepts, and solutions for improving refrigeration technologies along the European food cold chain (Eden & Colmer, 2010; Gogou et al., 2013; Evans et al., 2014a,b). The evaluation of barriers to energy consumption levels and benefits of implementing food security management systems, development of eco-efficiency indexes to qualify company performance, power management method in the sector, analysis of resource efficiency in companies, local food retail chains as method of energy reduction, among others, have been developed to help improving the energy consumption of agrifood companies (Hennigsson et al., 2004; Maxime et al., 2006; Muller et al., 2007; Karaman et al., 2012; Mundler & Rumpus, 2012; Nunes et al., 2011, 2014a,b, 2015, 2016; Santos et al., 2013; Campos et al., 2013; Neves et al., 2014; Silva et al., 2014, 2016; Gaspar et al., 2014, 2016; Gaspar, 2015). In addition, through the quantification of indexes related to the level of GHGs emissions applied to agrifood industries is possible to qualify companies according to their emissions performance. The life cycle analysis of a food product allows to analyze all aspects related to its sustainability (Plassmann et al., 2010; Ruviano et al., 2012).

Most of these authors are consensual on several best practices to improve the overall energy performance of agro-food industry. Recommended actions to reduce energy and maintenance costs, to improve facilities security, to increase productivity and competitiveness, and improve the environmental impact of a company can be gathered (Nunes et al., 2016; Silva et al., 2016):

- Improved building infrastructure (thermal resistance materials with proper thickness and/or good quality of the insulating materials, low thermal conductive roofing materials, open recesses, among others) and new layout design have a high energy savings potential.
- Cold rooms' insulation: Cold rooms should be built in polyurethane panels at least with 100 and 120 mm thick, respectively, for chilled and frozen food products. The doors of the cold rooms should be well insulated with seals in good conditions (periodic verification of cold doors' rubber seals should be performed) and remain closed as long as possible as an operative procedure to increase the energy savings. Similarly, lighting of unoccupied cold rooms should be turned off. Optionally, electronic controllers for lighting could be implemented. Finally, the replacement of incandescent lighting with compact fluorescent or LED lighting is strongly recommended. In relation to the management of food products inside cold rooms, a uniform product cooling should be achieved by a careful

distribution of products within the cold room, avoiding product placement close the cold air inlets, partial load of cold rooms, and exceeding the maximum storage capacity.

- Refrigerant ducts insulation: Avoid lack of insulation in refrigerant ducts. Old refrigeration system, mainly the compressor, should be replaced by new ones with high-efficiency motors. The condensers should be installed in shaded ventilated areas and cleaned regularly. The adequate (proper system) and regular (control system) defrosting of the evaporators is highly recommended.
- Periodic preventive maintenance procedures: Maintenance procedures should be regularly performed, such as detecting and repairing air leaks of compressed air systems, checking the operating parameters of steam generators, inspecting the regulator of boiler combustion, and cleaning of heat exchange surfaces.
- Energy-efficiency management: Several procedures may be taken such as the systematic analysis of energy bills to detect larger power consumers and power factor irregularities. Whenever possible, the use of renewable energy may be implemented. An energy management plan should be developed taking into account the above recommendation.

Several of these practice measures are very cost effective and provide significant energy savings. Most of these are related with regular checks included in maintenance, monitoring, and service tasks. The remainder recommendations have a large scope of paybacks.

8 Conclusions

This chapter provides an overview of the current food production methods and technologies in terms of energy use, environmental impacts, and sustainability. The evolution of food production processes and technologies is presented over time, from a stage where agriculture had a reduced or zero environmental impact to date, where this impact cannot be avoided, resulting from the intensive use of the soil, by way of deforestation, use of fertilizers, diverse machinery, among others. This chapter shows that human action on nature has left an indelible mark from the earliest days of the Industrial Revolution to the present day, leading to an increase in CO₂ content in the atmosphere from 280 to 375 ppb, from CH₄ from 715 to 1774 ppb and N₂O concentrations that increased from 270 to 319 ppb. Climate change resulting from this human action together with the excessive

use of pesticides causes difficulties and aggravates the problem of availability of drinking water on the surface of the planet as well as its quality. Of course, due to the intrinsic characteristics of each productive sector, as for example, the livestock production has not the same techniques, machinery, and tools as the cereals production, the corresponding environmental costs are different. The world cereal production was expected to reach 2571 million tons in 2016, and with an expected target of 3.0 billion tons by 2050, but, in fact, climate change can affect seriously these expected production values in a variety of ways such as long periods of drought or rain, extremely harsh winters and scorching summers, and plagues on crops. Another large sector referred to in this chapter is the livestock sector, which covers several types of products from food to clothing (meat, eggs, milk, honey, among others). The scope and field of action of livestock farming is gigantic, increasing the difficulty of evaluating the general environmental costs or their ecological footprint. Just the global production of meat is expected to reach 470 million tons in 2050, more than the double of the 229 million tons verified in 1999/2001. The amount of livestock's drinking water consumption: cows, pigs, sheep, and chickens in intensive farming was calculated, respectively, at 103, 17, 9, and 1.3–1.8 L/day. Approximately 8, 4, and 1 kg of cereals are needed to produce 1 kg of bovine, pork, and poultry meat, respectively. In fact, the increase in food production, especially regarding the increasing sources of high-protein foods to meet the future demand of the population, has certain challenges to face: there is not enough land for the expansion of livestock; if predatory ocean fishing continues, this activity may deplete resources for future populations; the high cost of feeding animals puts in debate if that food should be used for animals rather than being used for feeding starving population around the world; increased competition for water resources.

The dairy sector is another important livestock subsector referred to in the chapter. Products such as milk, cheese, and yogurts are consumed worldwide and are of paramount importance for people's food base. This industry branch is currently highly advanced in terms of technology, consisting of fully automated processes focusing on improved food safety. The milk production in the last four decades grew by 64%, reaching a value of 790 million tons in 2012 with the cheese production accounting by around 27% within this sector. This chapter also highlights the importance of food products in the horticultural sector, which apart from being the most consumed food products are also widely used as raw materials in various food industries (wine, olive oil, juice, and frozen foods). In 2009, the fresh vegetables

represented 24.4% of the horticultural products produced worldwide. The largest vegetable producers are Asian countries, particularly China, Japan, and India. The per-capita consumption varies from region to region of the world due to the eating habits and living standards of each country. For the coming years focus on sustainable consumption and sustainable production is required. In fact, sustainable food systems are key points to address food security, poverty alleviation, and adequate nutrition, and play an important role in building a society able to recover the balance between environmental and production costs.

Some noteworthy projections left in this chapter highlight the need for sustainable food systems: as population grows from 7.2 billion today to the prediction of 9 billion people by 2050; 30% waste of the total food production; 12.9% of the population in developing countries suffer from chronic hunger; it is estimated that 70% of the waters, large part of deforestation, and biodiversity loss was caused by agricultural production. The increase of local production and consumption, encouraging agricultural production activities in the cities and their surroundings, may contribute to mitigate the effects of global climate change.

Novel preservation technologies are an interesting option to produce high-quality food products with an extended shelf life. The starting point of an evaluation of the possibilities of novel technologies will therefore be the effect on quality combined with the safety of the product after processing. Interest in nonthermal food processing technologies has increased appreciably in the past decade. Current limitations of emerging nonthermal technologies can be overcome when they are combined with conventional preservation methods. Especially using higher or lower temperatures than room temperature is an interesting option to increase the effectiveness of novel technologies. Additionally, the development and implementation of emerging and innovative food processing technologies, as for example, joule heating and hydrostatic high pressure, are required to increase efficiency and production rates. Furthermore, the life cycle analysis of a food product constitutes a scientific working tool allowing to analyze all aspects related to its sustainability.

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ELUCIDATING LOCAL FOOD PRODUCTION TO IDENTIFY THE PRINCIPLES AND CHALLENGES OF SUSTAINABLE AGRICULTURE

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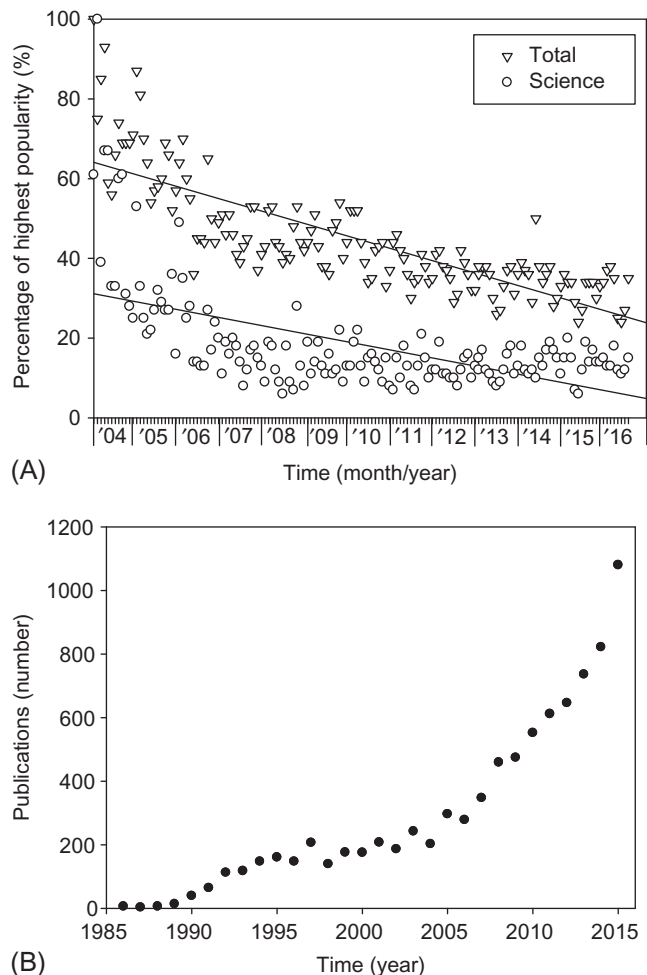
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1 Sustainable Agriculture—Definitions, Conceptual Framework, and Practical Applications

Sustainable development emerged in the last four decades as a widely used concept dealing with balancing environmental and human concerns. The concept focused primarily on the environmental and economic dimensions, but within a globally changing society, this concept cannot be completed without including social, political, and/or cultural changes and their interaction (Barnett, 2001). The importance of factors, such as poverty, social equity, and governance is currently gaining more recognition. Basic principles emerge from the international sustainability discourse such as the welfare of future generations, ecosystem well-being, and the achievement of an acceptable standard of human well-being (Assessment, 2005; Swart et al., 2003). Sustainable agriculture is emphasizing this balance in the initial phase of food production. Literature related to sustainable agriculture arose during the 1960s and has been expanding ever since. However, the popularity of the concept in the public discourse is apparently

Fig. 1 Trends in public interest and production of scientific papers of topics related explicitly to sustainable agriculture. (A) and (B) illustrate contradicting trends. (A) Trends in current interest regarding “sustainable agriculture” google search in the last decade. A value of 100 represents the highest search popularity for the analyzed time (2004–2016). This value is a ratio between the search for “sustainable agriculture” and total search in google. Hence, decrease in popularity may be a result of increased volume of total search. Yet, the relative popularity of “sustainable agriculture” show clear decrease according to this analysis. Science means categorized search, total is not categorized (Google Trends analysis for “sustainable agriculture”). (B) The number of scientific papers related to sustainable agriculture (ISI web of knowledge).



declining (Fig. 1) and academic encouragement for public participation in its development is not improving the public’s interest (Pretty, 1995).

The first challenge of every discussion of sustainable development is defining its scope and goals (Lele, 1991). We relate to sustainable agriculture as the economically viable production of food, fiber, and other uses of plants and animals that is environmentally sound, socially responsible, nonexploitative, and which serves as the foundation for future generations (Allen et al., 1991). Traditionally, agriculture is defined as manufacturing food from land, following the Latin compound *agricultura*, a combined word from *ager* (field) and *colo* (cultivate), which stands for land tillage. Nowadays, agriculture usually refers to a wider scope of activities:

domestication of plants and animals, horticulture (Harris & Fuller, 2014), aquaculture, and pastoralism. Agriculture commonly refers to the cultivation of plants and animals to provide food and additional services and products. Sustainable agriculture has arisen in response to the main issues of the current agricultural system, such as top soil depletion (Montgomery, 2007), groundwater contamination (Horrihan et al., 2002), deforestation, and the loss of habitat and biodiversity (Tilman et al., 2002). Additional concerns are the decline in family farms, and the disintegration of economic and social conditions in rural communities (Wezel et al., 2014). Discussing sustainable agriculture, we would like to expand the use of the term “agriculture” to include any foundational or initial steps in food production, even when it does not implicitly involve active land management per se. Another way to expand agricultural scale is to look at the wide ecosystem services that it supplies. Ecosystem services are an essential part of the total economic value of the Earth (Costanza et al., 1998). Ecosystem services are typically distinguished by four categories: supporting services, provisioning services, regulating services, and cultural services. Provisioning services are widely discussed in this chapter, whereas the other services are mentioned briefly. A comprehensive term for food and other natural products used by humans should include aquaculture (Frankic & Hershner, 2003; Naylor et al., 2000; Shumway et al., 2003), wild fishing and hunting (Berkes et al., 1994; Mena et al., 2000), rangelands and grazing, beekeeping, and gathering of plant products for pharmacology and herbs, for biomass, biofuel, fiber, and other uses. Long after Cox and Atkins (1979) have observed, “Agriculture activities have become the dominant ecological force over nearly one-third of lands areas of the earth,” it is now widely accepted that the tremendous impacts of agroecology should be addressed for a better understanding of ecosystem function and services and to solve problems that farmers face daily (Gliessman, 1990; Wezel et al., 2014). Well-developed literature is devoted to different aspects of sustainable agriculture, its history and current role (Harwood, 1990), principles of soil management (Pittelkow et al., 2015), and practices and future regulatory projections (Reganold & Wachter, 2016). Plants and animals serve additional needs besides being consumable products, or food for humans and other animals. Exploitation of animals include traditional practices such as transporter animals and labor force, animals used for hunting, service, biologic control, entertainment, and recreational activities. Herein, we focus on nonconsumable uses of plants. This illustrates how exploitation of biological goods includes a wide diversity of uses and services that humans receive from the biosphere.

2 Sustainability of Nonconsumable Uses of Plants

To discuss broadly the consequences of plant exploitation on the environment and the potential to enhance sustainability, additional uses of plants that should be considered are mentioned. In the last decades, the variety of plant uses is also expanding. For example, land management to decrease soil erosion, barrier plants in front of invasive species, cover crops, phytoremediation, maintaining constructed wetlands for wastewater treatment ([Shelef et al., 2013](#)), horticulture and decoration, fiber, biomass for fuel, and pharmaceutical uses. Plant-assisted bioremediation is a technology that exploits the synergistic action that occurs in the plant rhizosphere where microorganisms (bacteria and fungi) remove, convert or contain toxic substances in soils, sediments, and aquatic environments. The phyto-assisted bioremediation is an eco-sustainable strategy for the environmental recovery of areas affected by widespread contamination.

To give a clearer sense of what “sustainable agriculture” is, we are suggesting that sustainable agriculture stands on these four pillars ([Fig 2](#)):

- (1) land management,
- (2) resource management,
- (3) human interface, and
- (4) ecosystem interface.

The next paragraphs describe our understanding regarding these four pillars.

2.1 Land Management

Land management is an effort to use, develop, and maintain land resources. As the name suggests, land management concentrates on soil but most of the principles are also true for aquaculture. This section will focus mainly on land and soil properties. The main goal of conservation agriculture (or later on, regenerative agriculture) is to allow land use without overexploitation while preserving bioactivity ([Stinner & House, 1990](#)) through three crop management principles—(1) minimum soil disturbance (no-tillage), (2) permanent soil cover by crop residues or cover crops, and (3) crop rotation ([Pittelkow et al., 2015](#)). Many agronomical practices fall under the title of land management including agroforestry, intercropping, crop rotations, tillage management, and landscape management ([Wezel et al., 2014](#)). One of the main principles of sustainable agriculture is flexibility ([Lichtfouse](#)

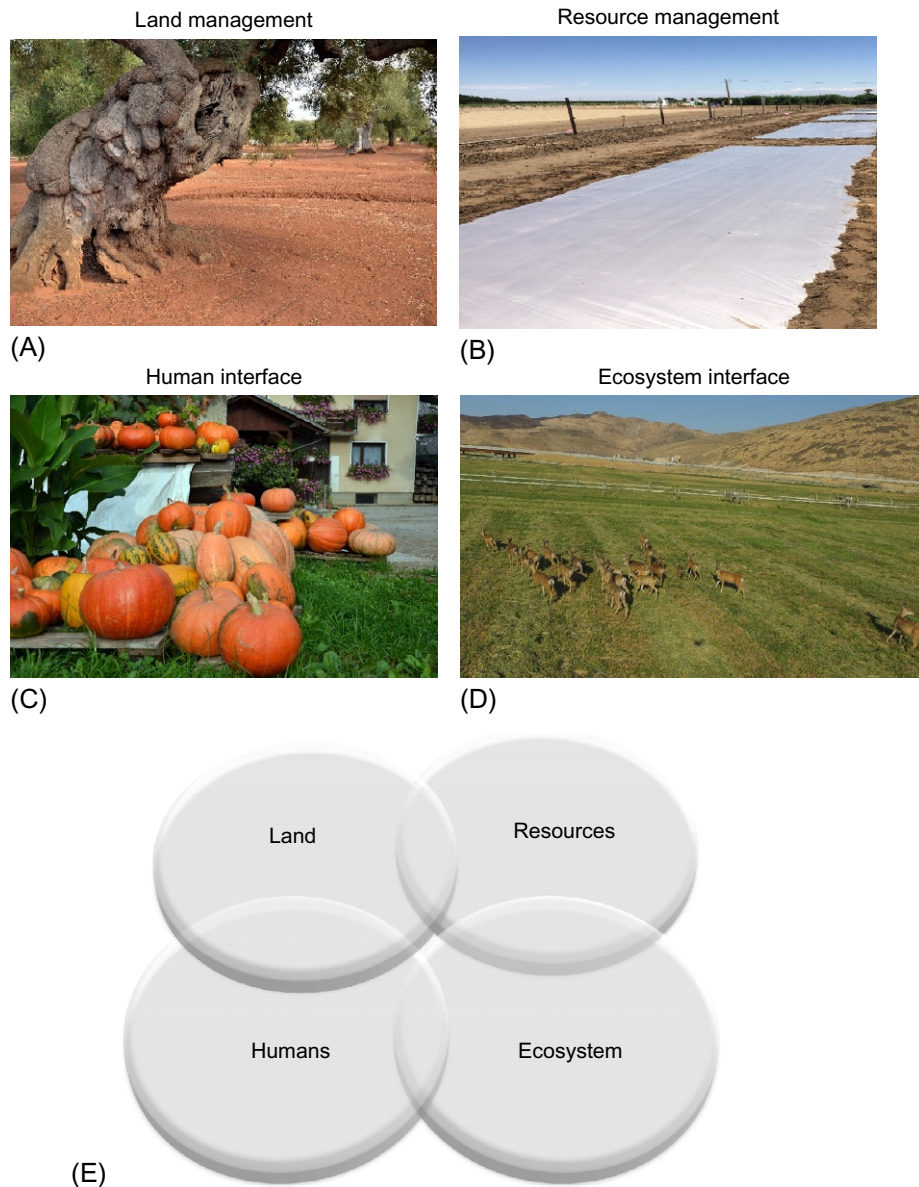


Fig. 2 The four pillars holding the concept of sustainable agriculture are demonstrated by self-explanatory photographs. (A) Old olive orchard is conserved near Ostuni, Puglia, Italy. The project integrates land and soil management, farmer training, commercial incentives, and agrotourism. (B) Biosolarized experimental plots in Parlier University of California, Kearney Agricultural Research and Extension, plots were solarized with the addition of tomato waste and digestat. (C) Pumpkins in a family garden are common in Slovenja. Smallholder farming systems provide food and additional assets as aesthetic values and self-physical maintenance. These assets advance the standard of living. (D) Deer herd in alfalfa field, Reno, Nevada. (E) A conceptual scheme of all four pillars. (A), (C), and (D) photos taken by Shelef O; (B) photo taken by Achmon Y.

et al., 2009). Land management is a practice with high degrees of flexibility and should be examined closely when practicing sustainable agriculture. Land management involves soil science, creative solutions to frequent agricultural problems and policymaking (Shelef et al., 2015). When considering the use of the land from the viewpoint of sustainable agriculture, questions about the long-run impact on soil, resources, ecosystem, human health, and society should be asked in addition to questions about yield and productivity.

Land management aims for resistant crops that are less vulnerable to abiotic stresses or enemies (pests, herbivores, and disease). Similarly, healthier soil that can be developed and maintained through the integrative management of plants, soil, water, and nutrients, decreases vulnerability of the agroecosystem. Furthermore, unbalanced crop management regimes may lead toward lower soil quality that often result in greater inputs of resources such as water, nutrients, pesticides, and/or energy. Soil organic matter plays a key role in soil quality; therefore, maintaining or increasing soil organic matter is a necessary part of sustainable agriculture. Carter (Carter, 2002) emphasizes the importance of organic matter to several soil quality parameters such as soil fertility, productivity, and erodibility. Moreover, soil is one of the main sinks for carbon in the earth (Todd-Brown et al., 2014). Sustainable agriculture practices such as compost incorporation, cover crops, intercropping, crop rotation, and sustainable tillage management can offer beneficial solutions regarding soil organic matter management. Lately, approaches that integrate elements of the natural landscape such as hedges, seminatural habitats conservation, vegetation strips are gaining popularity (Holland et al., 2016). Their role is to reduce pest outbreaks by providing habitats and overwintering sites as well as resources such as alternative prey for beneficial insects or other pest predators (Holland et al., 2016; Wezel et al., 2014). The long-term goal of sustainable land management is to integrate it with in-depth environmental assessment, which will allow the next generations to have the same or better benefits out of these lands.

2.2 Resource Management

To sustain land for future generations, agriculture is constantly seeking to reduce inputs and to utilize renewable sources that are more environmentally stable and more economically wise. Low external input farming (Liebman & Davis, 2000) include inputs such as energy, water, nutrients, and practices that fight pests, weeds, and pathogens. Many examples of renewable and

environmentally friendly resources can be found in the literature (Lichtfouse et al., 2009; Wezel et al., 2014). To minimize water-related issues, both policy and management actions should be considered. The main actions include

- (1) improving water conservation and storage measures,
- (2) promoting use of drought-tolerant crop species,
- (3) using low-volume irrigation systems,
- (4) managing crops and land to reduce water loss and need, or
- (5) assessing the suitability of planting.

From the point of view of sustainable agriculture, water has many feasible solutions in the policy realm. Managing nutrient cycles and pest control are also vital for the success of sustainable agriculture implementation. For example, biosolarization is an environmentally friendly way to disinfect the soil (Achmon, et al., 2016b). It can use streams of wastewater that come directly from industrial food processing, to treat the soil against pests (Achmon et al., 2016a). Biosolarization is an example of a practice that supports circular economics—an economic practice that implies that the same resource is utilized throughout the process (Oldfield et al., 2017). Other notable examples of circular or scarce use of resources include biofertilization, composting, drip irrigation, biological pest control, and more (Wezel et al., 2014). The production of food in hyperintensive yield levels is becoming a major part of advancing to a world that feeds more people with fewer inputs per area or per yield. Through constant improvement of renewable sources utilization by extensive research, sustainable agricultural practices can prevail over their industrial agricultural analogs in the future. The way to achieve this ambitious goal is through collaboration of interdisciplinary research groups that will use the recent advancements in fields such as bioinformatics, molecular biology, microbiology, ecology, and many others.

2.3 Human Interface

The interface between human demand and agriculture requires efforts to reduce pollution in the air, soil, and water spheres and improve socioeconomic-related issues in food production with an emphasis on human health and livelihood. The human interface is maybe the most unpredictable and complex of the four pillars as it is influenced strongly by personal values, culture, norms, and habits (Peattie, 2010). From a sustainable agriculture point of view on the direct and indirect impacts that agriculture has on humans, different questions may arise: Are these crops produced locally? Which population is most heavily impacted by agriculture? What are the health risks and are there

ways to reduce them? The major shift in perception on the impact that intensive agriculture practices can have on the environment came during the 1960s when Carson published her book “Silent Spring” (Carson, 2002). Nowadays, as more evidence is gathered on the negative health effects caused by pollution, the more the impact this pillar has on agronomical practices. Industrial agriculture is considered a large source of pollution, especially when it comes to livestock that involves large amounts of waste and extensive use of antibiotics (Horrigan et al., 2002). In that sense, sustainable agriculture can be used as a solution that would reduce waste and antibiotic/pesticide residues (Horrigan et al., 2002). Moreover, sustainable agriculture considers social responsibilities including working and living conditions of laborers, the needs of rural communities, and consumer health and safety both in the present and the future (Brodt et al., 2011). It also incorporates consideration of farmer goals and lifestyle choices. For example, adopting technologies or practices that promise profitability may also require intensive management, which could deteriorate the quality of life. We all share responsibilities in sustainable agriculture. Consumers also have a critical role. Their decisions on products will influence producers, retailers, and others. The challenge is to find strategies that integrate environmental quality, resource use, and social equity issues among their shopping criteria: food cost and nutritional quality.

2.4 Ecosystem Interface

Food production has enormous impacts on landscape and ecosystem services (Palm et al., 2014; Power, 2010; Zhang et al., 2007). Sustainable agriculture aims to reduce these impacts and maintain ecosystem services, biodiversity, and the livelihood of animals. The interface between agriculture and biodiversity or ecosystem function includes mainly land fragmentation (Carsjens & Van Der Knaap, 2002). Land fragmentation leads to negative impacts on wildlife (Bayne & Hobson, 1998). These include habitat loss, chemical leakage, and man-animal conflicts (Lemly et al., 2000). In addition, agricultural activity is expanding deforestation, contributing to greenhouse gas emissions, and enhancing genetic pollution. The growing concern that the world is entering its sixth “mass extinction,” this time derived mainly by anthropogenic activity (Ceballos et al., 2015), accelerates the need for far sustainability in agriculture. About 7000 species of plants in the world have been used for food, however, in the last 50 years, only six species cover 50% of the arable land: wheat, soybean, maize, rice, barley, and rapeseed (Jacobsen et al., 2015). Among the 100–120 crop plant species used today for extensive food

production, 95% of humans consume only 20 species. Land conversion from natural habitats to cultivated fields caused a great loss of native insect populations (Pyle et al., 1981). In 1999, the FAO (Food and Agriculture Organization of the United Nations) estimated that 30% of livestock breeds were at risk of extinction and six breeds were lost each month (FAO, 1999). The most popular actions toward sustainable agriculture include selection of species and varieties that are well suited for environmental conditions of the area, diversification of crops (including livestock), and cultural practices to enhance the biological and economic stability of the farm.

Current efforts to improve sustainable agriculture are facing serious difficulties. The main challenges with sustainable agriculture are maintaining low-input practice (e.g., water, nutrients, pest control, land, energy) without a significant reduction in yield (Pittelkow et al., 2015). These challenges correspond to the second pillar and different practices. Now, applications and technology of sustainable agriculture are numerous. Table 1 gives the relevant technologies that include precision agriculture, advanced irrigation management, integrated pest management, organic waste utilization, and more.

Table 2 describes the main challenges of sustainable agriculture, sorted by the four pillars—land management, resource management, human interface, and the ecosystem interface. One idea that could help resolve these challenges is to urge the public to “think globally and act locally,” a call that has been widely used by environmentalists since the 1970s. Essential implication of this call prefers the use of local food production on the import of exotic species.

3 Food Production from Local Species

The early days of agriculture, began about 10,000 years ago (Zohary et al., 2012), where people used local species and selected for desirable traits for human consumption (Diamond, 2002). Long before that humans were hunting and gathering local species for consumption. Domestication began with the cultivation of wheat in the Fertile Crescent of Turkey and rapidly spread all over Europe (Zohary et al., 2012). Humans have been exploiting plants, mainly for food, over thousands of years in which people vastly influenced plant evolution. Harris and Hillman (1989) recognized the main developmental steps of this relationship. First, the use of pounding stones to treat woody and hard tissues. Second, prescribed and controlled fires (slush and burn) and third, harvest seeds and storing them. The next developmental steps

Table 1 Main Practices, Concepts, and Technologies to Support the Four Pillars of Sustainable Agriculture

Practice	Potential Benefits	Challenge	Example	Reference
Precision agriculture	Super-intensive yield	High equipment cost	Reduce water supply	Lopes et al. (2011) , Engel et al. (1999) , and Thierfelder et al. (2015)
	Highly controlled inputs	Specialized workers	Distribute application rates of fertilizer N across the landscape and time	Hernández et al. (2013)
	Reduced inputs	No organizational memory yet	Use of highly controlled smart drip irrigation Moisture and crop state measurement using robots and remote sensing	Mulla (2013)
Waste management	Reduction of organic wastes in landfills	High cost	Application of biofertilizers such as compost	Birkhofer et al. (2008)
	Reduction of emissions	Chance for a cross-contamination	Valorization of organic waste as a substrate to enhance pest control in soil biosolarization	Achmon et al. (2016b) , Fernández-Bayo et al. (2015) , Birkhofer et al. (2008) , and Fernández-Bayo et al. (2009)
	Displacements of polluting and high-energy consuming chemicals	Not enough research on long-duration impacts	Use of vermicomposts as soil amendments to prevent pesticide pollution The use of treated wastewater for agriculture	Friedler (2001) and Shelef (1991)

Table 1 Main Practices, Concepts, and Technologies to Support the Four Pillars of Sustainable Agriculture—Cont'd

Practice	Potential Benefits	Challenge	Example	Reference
Improved irrigation	Lower water use	Can require a high initial capital	Non-tillage of the soil to reduce water use	Daccache et al. (2015) and Klein and Camara (2007)
	More efficient and accurate water use		Controlled drip irrigation	
	Lower energy consumption	Can be labor intensive		
	Integrated practices (e.g., fertigation)	Require in-situ data to apply accurate irrigation		
Integrated pest management	Less potential of pesticides and nitrates contamination			
	Better resilience to pests outbreaks	High cost	Control of weeds, pests, and diseases based on the introduction of natural enemies, pheromones	Porcel et al. (2013)
	Displacements of polluting and high-energy consuming chemicals	Can be less efficient than chemical treatments	Combined application of solar radiation and unstable organic matter (soil biosolarization)	Achmon et al. (2016a)
	Preservation of biodiversity	Diversity of pests	Use of native species as a barrier to pests and diseases	Porcel et al. (2013) and Rodríguez et al. (2014)
Genotype crop improvement				
	Acquired adaptations reduce inputs	GMO debate Need to be closely monitored not to lose any desired feature	Use breeding for assisted selection of Fusarium wilt-resistant plants	Abdallah et al. (2015) and Gao et al. (2015)

Continued

Table 1 Main Practices, Concepts, and Technologies to Support the Four Pillars of Sustainable Agriculture—Cont’d

Practice	Potential Benefits	Challenge	Example	Reference
Role of soil microbiology	Reduced stress on local species	Regulation Convert the enormous amount of genomic data into functional knowledge		
	Reduced inputs	Still need a lot of research to become applicable	Planting and management of vegetation strips and hedges in fields and at field borders	Mostafiz et al. (2012) and Tscharntke et al. (2007)
	Improved soils instead of overexploitation	Presence of opportunistic or even regular human pathogens, which are frequently found in endophytic communities		
New crops	Reduced inputs for species adapted to local conditions	Still need a lot of research	Fruit tree-based agroforestry systems	Bellow et al. (2008) and Tilman et al. (2002)
	Reduced allocation to transportation	Overcoming the cultural and public perception gap	Use of resistant crops to biotic and biotic stresses (and mixing them)	
	Respect for indigenous culture	Regulation		

were cooking, detoxification by leaching, and cultivation. The later ultimately caused some plants to lose their ability to survive and reproduce wildly without human interference. The main conclusions from Harris’ fundamental work are the following. First, the distribution patterns of current plant communities illustrate the habitat preferences of their progenitors more than they tell us about their origin. The second conclusion is related to the essential question—what makes one species a successful domesticated crop ([Diamond, 1999](#)). The authors concluded that

Table 2 The Main Challenges of Sustainable Agriculture

Pillar	Challenge
Land management	How to reduce habitat loss, ecosystem fragmentation, and soil erosion without decreasing crop yields
Low inputs	Increase water use efficiency Increase nutrient use efficiency Integrated pest control Increase energy use efficiency
Human interface	Produce food to more people Reduce negative impacts on human health Improvement of management: transparency, geo-justice, regulation GMO debate: safe use of genetically modified organisms
Ecosystem interface	Reduce impact on climate change Invasions and introductions Biodiversity crisis

comparative studies of plants in a given habitat would promote better understanding regarding which traits favored the success of a focal species. Third, [Harris and Hillman \(1989\)](#) described three pathways for domestication defined as “human intervention in the reproductive system of the plant resulting in genetic and/or phenotypic modification.” The three pathways of domestication represented by Harris and Hillman are: (1) reduced plant survival, (2) selection for gradual phenotypic change, and (3) phenotypically plastic changes or acclimation of plants without any apparent genotypic changes.

Thousands of years of plant domestication have led to extreme changes in the human diet, as well as social development, driving to a greater consumption of grains. Carbohydrates are still serving about 60% of our calories today ([Foster et al., 2003](#)), most of these carbohydrates are consumed as grains (mainly rice, wheat, and maize). Most domesticated plants and animals experience widespread expansion. Once domesticated successfully, these crops and animals expand rapidly and are used in areas where they did not originate. Clearly, the human diet has dramatically altered with increased domestication and is still changing today. Urbanization is involved with greater consumption of polished grains (bran layer removed), where rice and wheat are preferred over grains such as millet, more sugar, more animal products, and most importantly more food is consumed away from home ([Drewnowski &](#)

Popkin, 1997). The most productive agricultural areas of the modern world are almost entirely different from the nine centers of ancient food production—the origin of the main cereals (Diamond, 2002). To date, most research has been devoted to improving existing crops rather than recruiting local species. According to FAO, the most globally used food crops are (by order of importance): rice (*Oryza sativa*, origin: Asia) (Maclean, 2002), wheat (*Triticum aestivum*, origin: Levant), soybeans (*Glycine max*, origin: East Asia), sugarcane (*Saccharum* spp. Origin: south Asia), tomato (*Solanum lycopersicum*, origin: Central and South America) (Consortium, 2012), maize (*Zea mays*, origin: Mexico), potato (*Solanum tuberosum*, origin: Andes), vegetables (not specified), grapes (*Vitis vinifera*, origin: Mediterranean), apples (*Malus pumila*, origin: central Asia), banana (*Musa* spp., origin: Southeast Asia and Australia), and cassava (*Manihot esculenta*, origin: South America). There are numerous ways to achieve improvements of existing crops, e.g., artificial selection and breeding, agrotechnical approaches and genetic modifications (Lemaux, 2009). However, to a larger extent, new crops developed from local species are an exception (Shelef et al., 2016). In the United States, nearly all food consumption consists of exotic species, including wheat, alfalfa, soybeans, and rice (Pimentel et al., 2005). Intense agricultural practices to increase yield and grow these species in a new habitat were developed. These industrial agricultural practices are associated with ecological and environmental costs, which include reduction of biodiversity, accelerated land degradation, large fertilizer input, water contamination, and the spread of pesticides hazardous to human health (Horrigan et al., 2002). Future goals in agriculture also include establishing methods that will decrease the ecological and environmental impacts while providing enough food for the increasing world population (Pimentel & Wilson, 2004). Additionally, future agriculture will have to cope with the manifestations of climate change, including changes in the frequency and intensity of precipitation as well as increased occurrence of droughts (Howden et al., 2007) and the use of chemicals (Boxall et al., 2009). Developing new plant varieties for crop production might provide some of the solutions for future agriculture challenges.

The commercial use of new crops has great potential but also many risks, including financial cost (Pimentel et al., 2005), and the dangers of introducing or enhancing invasive species. Recruiting local species can increase crop development with reduced nutritional inputs, land management, and diversification of monocultures. Plant domestication has the ability to expand agricultural income, diversify food resources while conserving soil quality, reducing nutritional inputs, and by coordinating more locally adapted crops (Shelef et al., 2016). The domestication of local

plant varieties has potential for future agriculture research and development, which is discussed later in this chapter. Improving the use of local species should include policy to promote commercial harvesting of local plants (i.e. (Godoy & Bawa, 1993; Plotkin & Famolare, 1992), hunting (Caro et al., 2015), and fishing (Finley, 2011)). The use of invasive species for human consumption (Lai, 2013) and for environmental issues such as phytoremediation (Shelef et al., 2012) can also be used as a way to reduce the negative impacts associated with them.

To conclude, domestication of plants is one of the most influential processes in human history. It resulted in vast socioeconomic improvements and human development. According to Harris and Hillman (1989) the main trends are increasing in sedentism (settlement size and duration) population density and social complexity (from ranking to state formation). Plant and animal domestication has nearly completely stopped. In contrast, recent analyses suggests that new technology, economic, and environmental factors are the driving trends of increase in local production, manufacturing, and services, a process named “deglobalization” (Hammes, 2016). With the growing initiative to improve sustainable agriculture and—with modern science and technology—an expanding use of local animals and plants is calling for more attention. One example is plant use for phytoremediation.

4 Additional Uses of Local Biological Resources—The Case of Phytoremediation

As we mentioned before, an expanding array of services is dependent on biological resources. In continuation with our theme, where we suggest that local species should be adopted, we illustrate how local species may serve as biological sources for nonprovisioning services. Local plants are used for: land managements and for combatting soil erosion (Zuazo & Pleguezuelo, 2008), cover crops, phytoremediation, maintaining constructed wetlands for the wastewater treatment, horticulture, fiber, biomass for fuel, and pharmaceutical uses and green covers for buildings. Hypothetically, local plants are more likely to tolerate the local conditions and perform better with less energy. Herein, phytoremediation is used as an example.

Plants have the potential to metabolize some organic xenobiotic compounds in contaminated areas through phytoremediation, in a three-step pathway: activation, conjugation, and

compartmentalization (Vergani et al., 2017). Plant detoxification of hydrophobic chemicals, such as polychlorinated biphenyls (PCBs), is affected heavily by limited uptake capacity, due to the generally strong adsorption of these compounds to the soil organic matter (Schäffner et al., 2002). The local soil-plant microorganism community has a crucial role in the phytoremediation processes, marking the importance of using local plants for this goal. Plant-microorganism interactions can improve PCB degradation in the rhizosphere due to synergic interactions between roots and the natural soil microbial community (Ancona et al., 2016; Mackova et al., 2009; Sylvestre & Toussaint, 2011). Plant roots support natural microbial communities that transform, remove, and contain contaminants in the soil and in the so-called plant-assisted bioremediation (Wenzel, 2009). Several plant species (e.g., *Medicago sativa*, *Festuca arundinacea*, and *Glycine max*; see Zeeb et al., 2006) have high capacities to stimulate native soil-microbial populations to degrade toxins, which favor the restoration of PCB-contaminated soils (Leigh et al., 2006; Low et al., 2010; Meggo et al., 2013; Tu et al., 2011; Xu et al., 2010). For example, *Populus* tolerates high concentrations of metals because of its rapidly growing and deep roots. *Populus* has already been used successfully in the biodegradation of persistent organic compounds such as PCBs.

The selection of plant species for phytoremediation is a crucial step to ensure efficient recovery of the contaminated site. Choosing local plant species is strategic because they are more likely to thrive in local conditions (e.g., pH, organic matter, nitrogen and phosphorous content, moisture, porosity, etc.) and in the face of disease and pests typical of the area of interest. The supply of nutrients, water, and oxygen ensures a level of quality soil that is needed by plants that consequently increases the activity of soil microorganisms, which play a key role in phytoremediation.

Arborea or fast-growing herbaceous plants (like those used for purposes of soil reclamation) can supply raw material for a wide range of uses (e.g., production of biofuels, direct production of electricity, thermal energy, wood packaging, bioplastics, or biochar). Depending on the characteristics of the biomass, the market demand and conversion facilities in the area, it can be possible to plan/select the most affordable and sustainable exploitation. These concepts represent interesting future challenges that are in line with the main goals of the UE Communication “Towards a circular economy: A zero waste program for Europe” (COM (2014) 398 final/2).

5 The Main Challenges of Local Resources and the Potential of Sustainable Agriculture

While exportation of agricultural products occurs globally, there is still plenty of untapped local resources. This results in the same products being imported and produced globally. For example, importation of pine nuts to the western United States—the archeobotanical records dated pine nut gathering in Utah at least 7500 years before present (Rhode and Madsen, 1998). Today, the same *Pinus* species cover large portions of western North America. However, pinyon pines (mainly *Pinus monophylla*) in the West United States are not managed for pine nut production—in a \$100 million market, more than 80% of consumed pinyons in the United States are imported (Sharashkin & Gold, 2004), large amounts are exported from Russia. As a result, massive collection of pine nuts in Russia are slowly and continuously damaging the Korean pine broad-leaved forests (Ogureeva et al., 2012), thousands of miles away from California (Slaght, 2015). Pine nuts are not an exception—in a world motivated by economic short-term incentives and with almost unlimited transport anywhere, huge amounts of food are consumed very far from where they were produced. We stress that the use of local flora and fauna for food procurement and production reflects the concept of sustainable agriculture, its history, challenges, and its future. Indeed, environmental consciousness has been developing over the last decade in general, and specifically awareness on local food consumption. The newly invented term “locavore” (one who eats foods grown locally whenever possible) was marked the best word of the year 2007 by Oxford American Dictionary. The “locavore movement” emerged in San Francisco, calling to prefer local food consumption rather than distant resources, named “invasivore” attitude. This suggests that the discourse over local food production is gaining popularity. Table 3 illustrates the challenges associated with the use of local products in sustainable agriculture.

We compare and contrast two aspects of local production and consumption. First, we explain the advantages and disadvantages of using food that is produced and delivered in proximity to the place of its consumption. These products may not necessarily be native to the place of cultivation. Second, the development of innovative commercial value to the use of native plants and animals is described.

Table 3 How the Use of Local Biological Products Represent the Main Challenges of Sustainable Agriculture

Challenge	Reflection in the Use of Local Products	Reference
Land management		
Mitigate soil erosion	Native trees used as green belts to mitigate soil erosion and combat desertification Role of soil conservation in traditional cultivation methods No-tillage balancing weed control and cover crops; local cover crops to maintain soil health and fertility	Maathai (2004) and Prajapati and Tripathi (2008) Koulouri and Giourga (2007) Decker et al. (1994) and Yenish et al. (1996)
Reduce habitat loss and land fragmentation	Gathering and collection of local food Edible forest cultivation	Christensen et al. (2008) and Van Dijk et al. (2003) Chamberlain et al. (1998), Jacke and Toensmeier (2005), and Okafor (1977)
Low-input practice		
Water	Native plants are adapted to local conditions and require reduced inputs	Shelef et al. (2016)
Nutrients		
Pest control	Vast potential to recruit secondary metabolite of local plants Application of polyculture practices	Schmutterer (1990)
Energy	Proximity to food production reduces transport delivery inputs	Meisterling et al. (2009)
Human interface		
Produce food to more people	Local species have potential to open new markets and supply more food	
Reduce negative impacts on human health	Species adapted to their homeland habitats are more likely to require less chemicals	
Regulation	High regulatory cost for approval of new crops, processing system is sometimes incomplete	Kalaitzandonakes et al. (2007)
Transparency and geo-justice	Indigenous rights on biological resources	Brush (1993) and Posey and Dutfield (1996)
GMO debate	Natives provide source for adaptations, on the other hand they may be affected by GMO crops;	Dale et al. (2002) and Gasser and Fraley (1989)

Table 3 How the Use of Local Biological Products Represent the Main Challenges of Sustainable Agriculture—Cont’d

Challenge	Reflection in the Use of Local Products	Reference
Ecosystem interface	Climate change adaptation and mitigation	Paustian et al. (2016)
	Invasions and introductions	Pimentel et al. (2005) and Vitousek et al. (1997)
	New super cash crops are most likely to not remain local anymore	
Biodiversity crisis	Reduced impacts of traditional cultivation on biodiversity	Marjokorpi and Ruokolainen (2003) and Vidal (2008)

5.1 Advantages of Using Local Plants and Animals as Resources

In the developing world, about 10%–15% of approximately one billion hectares consists of traditional farming. These practices may offer insights relevant to all pillars of sustainable agriculture (Altieri, 2004) including conservation of biodiversity, soil, diversifying human diet, and low-input agriculture. The following are the advantages of using local species:

- (a) *Land and resource management perspective.* We posit that there is no difference between land management and the location of production and consumption. This means that the impact of preferring local production does not necessarily have a significant influence on land management. On the other hand, local plants are likely to mitigate soil erosion and reduce land fragmentation. In this respect, they might have a positive impact on land management. However, we suggest that the use of local species is more likely to impact resource management. Generally, the proximity of food production and consumption with each other implies that inputs are not transported to distant destinations, which support

recycling of minerals, water, and other inputs on site. This is likely to lead to a process with less waste and lower inputs of energy for transport, storage, and preservatives. Local plants are in favor of the resource management—low inputs of water, nutrients, pest control, and energy.

- (b) *Human interface perspective.* The human interface includes the potential to produce higher amounts and diversity of food for more people from new local species. Other aspects of the human interface with local species use are manifested in regulation issues, geo-justice, and the debate over the use of genetically modified organisms (GMO). Domestically grown crops supply fresher and potentially healthier food. The main reasons are reduced use of preservatives and reduced loss of nutritional values. Domestic production implies self-reliance and cutoff imports ([Little & Horowitz, 1987](#)), which promote society sovereignty. In addition, local production and delivery is promoting small-scale entrepreneurs, cultural diversity, sense of community, cultural and physiological context between people and food and link to natural seasonality.
- (c) *Ecosystem interface perspective.* At the ecosystem interface, the use of local plants and animals can reduce emissions, decrease hazards of invasions and introductions, and mitigate the biodiversity crisis. Transport infrastructure has an enormous impact on ecosystem fragmentation. Hence, the smaller the production-consumption circles, the smaller the impacts of fragmentation ([Gehring & Swihart, 2003](#)). Other issues include the spread of disease and the effects of invasive species on global agriculture activity, compared with local food production, which is less likely to involve both topics.

5.2 Advantages of New Crop Development

We suggest that there needs to be more research allocated to the development of new crops from native plants and animals, which will be advantageous to all four pillars of sustainable agriculture. The following include the benefits of using native local biological resources in light of the four pillars of sustainable agriculture.

- (a) Land management perspective

- (1) Conservation of plant-microbe-soil interactions: Soil is a vital component of agriculture, as water and nutrients are provided by soil and pass through the soil matrix to plant roots. Consequently, the physical and chemical properties of soil can greatly affect the supply of water and nutrients

and ultimately control plant growth. Soil microfauna also has a major role in shaping the chemical and physical properties of soil. For example, microorganisms shape the chemical properties of soil by controlling the cycling of various chemical elements in the soil, such as nitrogen and carbon. In addition, microorganisms have the capacity to shape soil physical properties, such as soil-water interactions and soil aggregation, by producing EPS (extracellular polymeric substances) (by soil bacteria) or fungal hyphae. Efficient interactions between plants and soil dwelling microbes are an important factor for plant growth, and it is more likely that local plants are adapted to local conditions and hence will interact efficiently with the local soil microbes. A growing number of studies have shown the importance of bacteria, fungi, endophytes, and rhizobia in the rhizosphere and plant tissues (Hawkes et al., 2007; Balestrini et al., 2015). These findings suggest that the role of underground interactions of plants with other organisms may have been underestimated (Shelef et al., 2013) and have a great potential to improve plant performance and crop yields (Drinkwater & Snapp, 2007). Mutualistic associations take time to arise. Therefore, it is more likely that the advantages of an optimal holobiome (sum total of all genomes in a living system) will be easier to maintain in the plant-rhizosphere-soil continuum that were developed in the same origin, than in a mixture of soil, plant, and other inputs derived from different and distant locations that are not locally adapted.

- (2) Incorporating local crops as temporal and spatial intercrops for land management: Plants may also be used in agricultural practice not just for the benefit of food production. Various plants are grown between fields and seasons to maintain soil quality and prevent soil degradation. Choosing the most appropriate intercrop is not necessarily taking into account the origin of the plants in use. No-tillage strategy is based on the local available plants. Other factors to consider are the advantages of the intercrops in maintaining soil quality, enhancing nitrogen uptake (Eaglesham et al., 1981), repelling herbivores and other enemies (Tonhasca & Byrne, 1994), reducing weeds (Liebman & Dyck, 1993), and offering overall a higher net income to the farmer (Yildirim & Guvenc, 2005). Local plants as intercrops have inherently two prominent advantages—local adaptation is likely to establish with little maintenance and the hazard of surging invasive species is avoided by using noninvasive species.

- (b) Resource management perspective
- (3) In addition to the above-mentioned benefits of any local food production, native plants and animals are adapted to the habitat and therefore are prone to be more efficient in surviving and producing high yields with less water, fertilization, pest and disease control, and so on.
- (4) Promoting genetic diversity: During the historic process of plant domestication in the last 10,000 years, favorable agriculture traits have been selected in all domesticated crops. As a result of this process, domestication created a bottleneck of genetic diversity, as numerous genes were selected out ([Vigouroux et al., 2005](#)). Limited diversity of crops project risks of disease and failure to adapt to changes in climate conditions. Native populations serve as a genetic bank that can enrich crop diversity. [Reif et al \(2005\)](#) reported how the loss of wheat cultivar diversity from 1950 to 1989 shifted to enhanced diversification through 1990–97, meaning that genetic diversity may increase if the genetic seed bank is preserved. Increasing genetic diversity of crops will promote resistance in front of adverse environmental conditions and stress ([Palmgren et al., 2015](#)). This notion accounts for the continuous future development of globally used crops and it emphasizes the importance of the conservation and management of local species.
- (5) Enhancing the diversity, endurance, and resilience of existing crops, using genetic diversity of native progenitors or crop recent relatives that preserve the desired traits: For example, [Cox et al. \(2006\)](#) elaborate on the benefits of perennial crops by breeding and domestication of perennials. Cox et al. describe the difference between the diversity of perennial plants in the terrestrial biomes and dominance of monocultures as annual crops (2006). The authors emphasize that today there are no perennials that produce adequate grain yield, although they tend to store more carbon and require less resources. Breeding in perennial crops has been initiated in several grain crops including wheat, sorghum, sunflower, and wheatgrass ([Cox et al., 2006](#)).
- (6) Science can expedite processes that a few millennia ago took centuries to develop, for example, improvement of food quality and resilience: Science opens opportunities that were not affordable before. [Diamond \(2002\)](#) stresses that knowledge regarding the control of bitterness will allow selection for fruits that were not edible before, for example, acorns.
- (7) Plant diversity should also be maintained in the context of their holobiome, representing not only the genetic variety of

the individual plant genome but also the metagenome including associated fauna, such as the microorganisms in the rhizosphere and the phyllosphere, which contribute to efficient plant growth under various environmental conditions (Pérez-Jaramillo et al., 2016). A metagenomics perspective can help to protect against emerging plant diseases and pests, and can potentially reduce the use of hazardous pesticides.

- (8) Arthropods should be used as an innovative local food source (*Anthropo-entomophagy*). Scorpions, beetle larva, crickets, termites, and many other arthropod species are an important part of the diet and culture in many non-European cultures (Van Huis et al., 2013). Recently, mass production of arthropods as food has been gaining popularity (Rumpold & Schlüter, 2013). Evidence shows that mass production of arthropod-based protein is more efficient (Premalatha et al., 2011), reduces pesticide use, reuses agriculture waste, and preserves the landscape and biodiversity (DeFoliart, 1997).
- (c) Human interface perspective
- (9) Diversifying commercial uses, dietary options, and income by recruiting new local foods and crops.
- (10) Reducing human interface-associated conflicts such as overexploitation of labor force in developing countries and fair trade: An example of a human interface issue is the case of the worldwide market of the quinoa grain. Although this case does not represent a domestication of a new plant species, but rather the controversy of how opening a market of a localized plant species to the international markets (Jacobsen, 2011). Jacobsen argued that the increased demand for quinoa put too much stress on the environment in Bolivia, leading to damaging land, biodiversity, and fair trade.
- (d) Ecosystem interface perspective
- (11) Reducing the negative impacts of introduced species: Invasive species tend to spread and damage the environment, threaten biodiversity, agriculture, and human health (Schmitz & Simberloff, 1997). Among some of the more damaging invasive species, insect outbreaks transform ecosystems (Foucaud et al., 2010); mammalian population outbreaks damages ecosystems and risk human safety (Côté et al., 2004); and weeds are adversely impacting rangelands across the United States and worldwide at an alarming rate (DiTomaso, 2000; Duncan et al., 2004). Recently, the EU Council adopted regulations on the prevention and

management of invasive species (PE-CONS 70/14, 13266/14 ADD 1), suggesting that out of 12,000 alien species in Europe, 10%–15% spread and cause damage, estimated at 12 billion euro per year. Clearly, the use of local species could alleviate these issues.

In summary, there are advantages to using local plants and animals for food production. Enhanced use of local plants will diversify agriculture entrepreneurship and preserve genetic diversity to enhance crop endurance during stressful environmental conditions. Local species in agriculture will reduce input investment and environmental conflicts. Even if local species are not economically relevant, it is critically important to maintain a diversity of plants from different geographic regions, which are relatives of the current, commonly used agricultural plants. Plant diversity possesses a myriad of ways to respond to adverse environmental conditions. These adaptations have developed over thousands of years. Seed-bank collections can provide a genetic resource to grow plants in various environmental conditions in different geographic areas or due to climate change ([Dempewolf et al., 2014](#)). If the benefits of using local species outcompete the use of global crops—why are they not used more frequently? Here we present what may be the main causes to this issue.

5.3 Obstacles Recruiting New Local Crops

Despite the advantages, recruitment of local new crops is extremely challenging and rare. These are the main obstacles and challenges that in our opinion explain why relying on more local food is still a potential future and not an existing globally wide practice:

- (a) Land management and resource management perspectives
 - (1) Intensive agricultural demand is selecting for cash crops at the expense of developing new crops with lower environmental impact.
 - (2) Once established, it is most likely that a new crop will rapidly spread and will not be local crop anymore.
- (b) Human interface perspective
 - (1) Conservative crop market: With infrastructure, machinery, companies, families, roads, and customers relying on a well-known food production, it is unlikely that any of the involved players would be interested leaving the familiar system and take the risk to invest in a new crop.
 - (2) Domestication is dependent on financial investment and has high risk. This implies that modern domestication

may flourish only with proper support of policy makers or strong financial interest.

- (3) Regulatory barriers for new crops: New foods require the approval of government agencies. Only several countries have proper systems to analyze the health risk involved with the consumption of new food items. Most governments rely on a few protocols and lists of edible species that are produced only in strong countries. It is highly likely that the regulator will eventually avoid giving high priority to invest in a risky process, leaving the entrepreneur missing the permissions to produce new food.
- (4) The use of local species may give rise to intellectual property concerns (Ahmed & Johnson, 2000).
- (5) Exploitation of indigenous people rights (Lee, 2013) may hinder domestication efforts. Indigenous communities tend to protect their resources and this can raise conflict when other people want to share their experience.
- (6) Health risk: Cordain et al. (2005) stressed that the human genome is not adapted to the diet in the Neolithic and Industrial periods. They explain that the western food have changed the key nutritional characteristics of human diets. More dairy products, refined cereals, sugars, and oils are underlying cause of many of the diseases of western civilization. Similar and other health issues should be considered with any novel food resource.
- (7) Moving to cultivation of food that was formerly collected in the wild nature may generate a debate on the effects of the new practice on rural farmers and harvesters (Stewart & Cole, 2005).
- (c) Ecosystem interface perspective
- (8) Risk of overexploitation: The massive use of local species must involve a thorough study of the ecosystem, species biology, carrying capacity, and interaction with other species. For example, moss is harvested in the western United States mainly for horticulture purposes. Peck and McCune (1998) raised questions regarding the balance between exploitation and natural regeneration of the harvested species. Similarly, local species in oil palm agriculture are used, but estimations offer that 60% of this plantation is at the expense of natural forests, threatening its unique biodiversity (Koh & Wilcove, 2008).
- (9) Biological barriers to domestication: Only a minority of potential animals and plants were ultimately domesticated. For example, only 14 of the 148 existing mammalian herbivores weighing at least 45 kg were domesticated (Diamond,

2002), or 20 from 200 according to [Kyle\(1994\)](#). When it comes to domestication of wild mammals, [Diamond \(2002\)](#) counted six reasons: slow growth rate, bad temperament, limited breeding in captivity, no leader hierarchy, and stress in enclosures. Similarly, only a handful of plants were domesticated successfully in modern times. [Diamond \(2002\)](#) mentioned strawberries, blueberries, macadamia, and pecan nuts as examples, which all had negligible value as compared with ancient domesticated plants.

- (10) The use of only local varieties may result in the disappearance of cultivars that are in support of sustainable agriculture principles. For example, Oriental wheat *Triticum turanicum* Jakubz ([Grausgruber et al., 2005](#)) is praised for its high nutritional value of a pure ancient stand. Avoiding the use of this cultivar just because it is expanded far from its area of origin (Anatolia, according to [Gökgöl, 1961](#)) would have contradicted many other aspects of promoting sustainable agriculture.

6 Conclusion

We refer here to agriculture as a more complex system other than the traditional plant cultivated fields. Agriculture is no longer a secondary drive of global dynamics and it has a strong impact on the environment: soil and water quality and quantity, deforestation, habitats and biodiversity, intensive farming, economic, and social conditions in rural communities. Sustainable agriculture has arisen as a reaction to the negative effects of agriculture standing on the four pillars: (1) land management, (2) resource management, (3) human interface, and (4) ecosystem interface. It seeks to sustain land for future generations by developing and maintaining land resources and soil properties. Agricultural practices should move from external-input farming to low-input practices (e.g., water, nutrients, pest control, land, energy) without significant reduction in production ([Pittelkow et al., 2015](#)) to feed the growing population. A wide diversity of available and emerging technologies is listed in [Table 1](#). The human interface is responsible for integrating these practices. The complex and unpredictable human interface is influenced strongly by values, culture, norms, and habits ([Peattie, 2010](#)). Small changes in the consumer culture can significantly reduce the environmental impact. For instance, reducing meat in the diet ([Eshel et al., 2014](#)) or preferring traits as taste and nutritional

value above visual appearance to reduce waste. One of the greatest challenges in agricultural sustainability is reducing the distances between crop, food production, and food consumption. The expanding and intensifying farming has already been contributing massive greenhouse gas emissions (crop and livestock production, in 2010 contributed $11.2 \pm 0.4\%$ of total greenhouse gas emissions), which is more than deforestation that contributes to only 8% of the total anthropogenic emissions (Tubiello et al., 2015). Considering the entire food production chain, carbon print is even higher, but with careful practice it can potentially sequester up to 15% of the global carbon emissions (Lal, 2004). To date, most research and practical efforts are devoted to improve existing crops rather than recruiting new and local species, to increase yield. The consequences are loss of biodiversity, accelerated land degradation, high fertilizer input, water contamination, and the spread of pesticides hazardous to human health. We need to change global monocultures toward more diverse local crops and domestication of new species, which is a promising tool to save biological resources. Local does not necessarily mean native, thus, using food products that are grown, harvested, stored, and delivered near the place of their consumption is advantageous. Native plants and animals require lower inputs of water, nutrients, pest control, and energy. Nevertheless, the long road toward local species use still has many obstacles to overcome. First, as we mentioned before, biological barriers to domestication are always a challenge. In addition, the global crop market makes it difficult to establish new crops. There are also barriers such as financial investments, regulation, and intellectual property concerns. Moreover, a successful new crop is highly likely to spread rapidly across the globe, losing its local value. This can create new issues such as fair trade and resource overexploitation. Therefore, new local crops must be integrated carefully. The advantages of using local plants and animals for food production are colossal. They will allow for diverse agriculture entrepreneurship, preservation of genetic diversity to enhance crop endurance in adverse environmental conditions, reduce input, reduce conflicts over indigenous land management, reducing environmental conflicts, and intercropping for improved land management. It is hard to project if the deglobalization trend is expected in the near decades for economic, social, technologically, and environmental reasons. However, we conclude that local food production should receive more attention in research and application to initiate and empower more sustainable agriculture.

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ROLE OF EARTHWORM IN SUSTAINABLE AGRICULTURE

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1 Introduction

Human beings always equate their well-being with consumption. Therefore, every nation rich or poor is in a race to increase production. This in turn is putting a burden on the environment due to misuse or overuse of natural resources. Actually around 60% of the total waste generated from industrial, agricultural, or domestic sectors is biodegradable and can be used for production of economically important plants and nutritionally balanced animal proteins. Vermicomposting is one such technology that synergizes microbial degradation with earthworm's activity for reducing, reusing, and recycling waste materials in a shorter span of time. Mutual action of earthworms and microbes brings faster decomposition as earthworms aerate, condition, fragment, and enhance surface area of the organic matter for microbial action. Importance of earthworm in the ecosystem was documented very early by Aristotle, the Greek philosopher who called them "*intestines of the earth*" and then in 1881 Charles Darwin highlighted their role in breakdown of dead plant as well as animal matter. The product obtained by the modulation of organic waste in the earthworm gut is quite different from its parent waste material and is also known as black gold or vermicast (Patangray, 2014). Vermicompost acts as a buffer, it has a significantly lower volatile solid and high N, P, and K content in the plant available form (Edwards, 1998). Large quantity of plant hormones such as gibberellins, auxins, and cytokinins are also present in vermicompost that promote growth of plants (Tomati et al., 1983).

Sustainable agriculture is the production of food from plant or animals by using different agricultural techniques that protects

the public health, human communities, environment, and animal welfare. During Green Revolution, an extensive quantity of chemical pesticides and fertilizers were used to boost up crop yield from agricultural land (Datta et al., 2016), which resulted in good yield and productivity. However, during the last four decades, the efficiency of the soil is getting reduced (Gupta et al., 2014; Vanita et al., 2014). The use of modern agricultural techniques has caused a steep fall in the number of biodiversity associated with cropland ecosystem (Beketov et al., 2013). Factors such as land use pattern, nitrogen enrichment, and climate change have also been reported to cause a change in soil biodiversity (Bardgett, 2005; Singh et al., 2016a). Soil biological properties have seldom played a role in agriculture assessment (Van Eekeren et al., 2010) but soil biodiversity contributes greatly to the efficiency of the resources use, suppressiveness, and provide resistance against disturbance and stress (Brussaard et al., 2007). In agriculture system, various activities have been performed by soil organisms such as recycling of nutrients, control of local microclimate, detoxification of chemicals, and regulation of abundance of undesirable organisms. The persistence of soil organisms depends on the maintenance of biological integrity and diversity in agroecosystem (Altieri, 1999). Soil biota are key players in providing nutrients through soil organic matter decomposition, nutrient cycling, promoting soil structure, and maintenance and play an important role in promoting plant growth (Wardle et al., 2001). Main issues related to agricultural development are the attention of public health and proper use of natural resources. Pesticides and herbicides sprayed in agricultural fields may affect the nontarget organisms such as earthworms and damage the ecosystem. Earthworms and its metabolic products (vermicast) may work as a driving force in sustainable food production as they improve soil health and fertility, protect crop plants from pests and diseases, increase plant growth parameters and nutritional quality. To overcome the dangerous effects of modern day agriculture, development of a farming system that is economically productive and long lasting in sustainable farming and inculcates inexpensive practices such as vermitechnology is the only permanent and cheapest solution (Gupta et al., 2014). This is the only key to a quick change over to sustainable agriculture without loss of crop yield. The current trend in agriculture is to seek sustainable practices which provide farm profitability.

The permanent and cheapest solution to overcome the hazardous effects of modernized agriculture is to develop a farming system that is economically productive and long lasting by simple and inexpensive practices by introducing earthworms.

2 Earthworm as Ecosystem Engineers

Earthworms are one of the most important soil animals that have the capability to maintain soil fertility, thus playing a key role in sustainability. The earthworm has an important role in soil formation and its contribution to the composition and functioning of soil ecosystem with varying species diversity; hence, they are known as ecosystem engineers ([Jones et al., 1994](#)). Earthworms enhance the incorporation of plant residue into soil aggregates, create soil porosity, and stable aggregate through their burrowing, humus formation, casting activities, and also affect organic matter localization in the soil ([Lavelle and Spain, 2001](#); [Bossuyt et al., 2004](#); [Jouquet et al., 2006](#)). The moderate number of earthworm in soil is beneficial and soil health is improved by way of efficient recycling of organic residue. Earthworm friendly, agriculture practices are to be developed to maintain their population in soil for long-term soil productivity ([Rajkhowa et al., 2015](#)).

Earthworms have the ability to digest and convert low-quality organic matter into a nutrient-rich product by developing mutualistic relationship with soil microflora ([Singh et al., 2014](#)). Traditionally soil organic matter has been evaluated in terms of C/N ratio. The amount and availability of essential biological nutrients, N, P, and K, are the key regulator of carbon process and could limit crop productivity. The feeding and casting activities of earthworms deposit organic remain into the soil. The population density of earthworms is lower and less diverse in arable soil as compared with uncultivated habitat. The activity of earthworm also enhances nutrient cycling, formation of humus and help in soil structural development ([Datta et al., 2016](#); [Singh et al., 2016b](#)).

The gut of earthworm contains many exogenic and endogenic enzymes to convert organic minerals into more exchangeable and available forms to plants ([Suthar, 2012](#)). Cast production in earthworm is an indicator of burrowing and soil turnover because 99.9% of ingested material is egested as cast ([Chaudhuri et al., 2009](#)). Vermicast increases the water-holding capacity, porosity, and softness of soil thus requiring less tillage and irrigation. Addition of earthworms and vermicompost to soil maintains an optimum level of soil media in terms of metal concentration, aeration, pH, and electrical conductivity ([Pathma and Sakthivel, 2012](#)). It is also rich in microbial diversity, nutrients, plant growth regulators (PGR) and has properties of inhibiting pathogenic microbes.

3 Composting Versus Vermicomposting

Composting and vermicomposting are the two best-known processes for the stabilization of solid organic wastes (Table 1). The difference between ordinary composting and vermistabilization is that heating above 35°C is necessary for the former but must be avoided in the latter, as it is lethal to the worms (Mitchell, 1979). Meunchang et al. (2005) reported that excessive composting could lead to loss or immobilization of nutrients such as nitrogen and phosphorus.

The combination of composting and vermicomposting is nowadays considered as a better way of achieving stable products

Table 1 Composting Versus Vermicomposting

S. No.	Parameters	Composting	Vermicomposting
1.	Temperature	Thermophilic 45–65°C	Mesophilic: 25–40°C
2.	Rate of degradation	Slow	Fast
3.	C:N Ratio	High	Low (<20)
4.	Space requirement	Require much space	Require less space
5.	Phases	(a) Thermophilic phase: quick degradation, elimination of pathogenic microorganisms. (b) Maturation phase: decrease in temperature, organic compound degraded at slower rate	(a) Active phase: modification of physical and microbial composition of waste. (b) Maturation phase: earthworm moves towards fresher layers of undigested waste, microbes already initiated decomposition of waste
6.	Action	By microbes	By microbes and earthworms
7.	End product	Slightly heterogeneous, stabilized humus-like material	Stabilized, homogenous, finely divided peat-like material known as vermicast
8.	Use	Well established on industrial, agriculture, and dairy waste	Not fully adapted on industrial scale
9.	Drawbacks	Volatilization of NH ₃ during thermophilic process	Requirement of maintenance of mesophilic temperature; neutral pH and high humidity for survival of earthworms
10.	Nutritional content	Low	High
11.	Economy	Cheaper	Costly

since it reduces the expenses as well as the duration of the treatment process (Tognetti et al., 2007). The effectiveness of the active phases of composting and vermicomposting as well as their combination for reducing the polluting potential and stabilizing of cattle manure in a short term was studied by Lazcano et al. (2008). The combined activity of earthworms and microbes promoted retention of nitrogen and gradual release of phosphorus along with a reduction in electrical conductivity and a better-quality product for agricultural use (Bajsa et al., 2003).

Earthworms help to maintain aerobic condition with optimum moisture and temperature in the degradation piles (Edwards, 1988). Contreras-Ramos et al. (2005) reported that the numbers of human pathogens in vermicompost was greatly reduced, an effect obtained in traditional composting due to rise in temperature. The survival of pathogenic organisms such as *Salmonella*, *Shigella*, fecal coliform, and helminth eggs was eliminated after vermicomposting of sewage sludge and human feces, proving that these pathogens were completely digested as they passed through the gut of earthworms (Rodriguez-Canche et al., 2010; Yadav et al., 2010). The reduction of pathogen numbers has been correlated to the release of coelomic fluids by the earthworms during vermicomposting, as it possesses antibacterial properties and kills pathogens (Sinha et al., 2002).

4 Composting Earthworms

The beneficial role of earthworms in the breakdown of dead plant material in the forest litter was documented first by Darwin (1881). It is believed that earthworms evolved about 570 million years ago (Sathe, 2004) and since then have been helping in conserving the natural environment. According to Kooch and Jalilvand (2008), there are in total 3627 species known worldwide. India is one of the important mega biodiversity countries and only 11.1% of earthworm diversity is available out of total global earthworm's diversity (Suthar, 2011; Chaudhari and Nath, 2011). It includes about 408 species placed in 10 families and 69 genera (Dash, 2012). In 1977, Bouche classified the earthworms into three categories on the basis of ecological distribution in soil (Table 2).

- (A) *Epigeic earthworms*: They are small sized, with uniform body coloration, live on surface litter or dung, and tolerate variable range of temperature. They have insignificant role in humus formation. These species are good for vermicomposting. Examples include *Eisenia fetida*, *Dendrobaena rubida*, *Perionyx excavatus*, and *Eudrilus eugeniae*.

Table 2 Characteristics of Different Type of Earthworms Under Different Ecological Categories

Characteristics	Epigeic	Anecic	Endogeic
Habitat	3–10 cm live in upper layer of soil	10–30 cm litter dwellers	30–90 cm deep burrowing
Feeding habit	Feed on leaf litter and animal excreta	Feed on litter and soil	Feed on organic matter present in soil
Burrow habit	Do not construct burrow and remain active in litter layer	Construct vertical burrows	Construct horizontal burrows
Body size	Small	Medium	Large
Regeneration capacity	High	Moderate	Limited
Pigmentation	Richly pigmented	Lightly pigmented	Low pigmented
Sensitivity to light	Low	Moderate	High
Fecundity rate	High	Moderate	Low
Efficiency in waste recycling	High	Well established in some	Not known
Casting activity	Surface casting loose and granular	Surface casting loose and granular	Thick and long casts

(B) *Anecic earthworms*: They are large sized with pigmentation only at the anterior and posterior end. They are mostly phytophagus and play a useful role in mixing nutrients from deep layers to surface by casting. Examples include *Lampito mauritii*, *Aporrectodea longa*, and *Lumbricus terrestris*.

(C) *Endogeic earthworms*: They are large- or small-sized worms with weak pigmentation. These are geophagus and found in the soil layer with organic and mineralized matter. Examples include *Metaphire posthuma*, *Octochaetona thurstoni*, *Allolobophora caliginosa*, *Aporrectodea rosea*, and *Octolaseon cynaeum*.

In 1985, Lee, however, classified earthworms on the basis of their feeding habits into two groups:

(a) *Detritivorous earthworms*: Earthworms feed at or near the soil surface and mainly feed on plant litter or dead roots or mammalian dung. Examples include *Eisenia fetida*, *Lampito mauritii*, *Perionyx excavatus*, and *Eudrilus eugeniae*.

(b) *Geophagus earthworms*: They feed deeper beneath the surface of soil and ingest large quantity of organically rich soil. Examples include *M. posthuma*, *Octochaetona thurstoni*.

5 Interaction of Earthworm With Soil

Earthworms significantly modify the physical, chemical, and biological properties of soil in which they live. The increased growths of crop in the presence of earthworms were the result of interaction between the earthworm species and different soil texture (Doubé et al., 1997; Lavelle et al., 2006). The organic matter provided was very accessible to microorganisms and earthworms allow a more sustainable management of these agrosystem than conventional agriculture. Briones et al. (2011) reported that addition of organic fertilizer has a positive effect on the earthworm biomass, C and N mineralization, and nutrient availability such as Mg, K, and assimilate P. They can increase soil porosity by creating burrows and reorganize soil structure by ingesting and egesting the soil while rearranging linkages responsible for soil aggregate stability (Shipitalo and Le Bayon, 2004; Jouquet et al., 2008a). Soil passage through earthworm digestive system lead to the assimilation of organic matter by earthworms and bacteria ingested with soil. This modifies the chemical properties of newly formed aggregates. Physicochemical properties of earthworm cast are also altered by changes in the microbiological activities that increase organic matter mineralization within cast and therefore increase nutrient availability (Singh et al., 2016b). These physical, chemical, and microbiological modifications generally result in an increased plant growth at least partially due to the release of mineral nutrients in earthworms cast.

6 Earthworm as Colonizers of Natural and Cultivated Soil Environment

The contribution of earthworms to the composition and functioning of soil ecosystem with varying species diversity has been explained by various workers. Human plays a dominant role in earthworm introduction and redistribution by transporting soil and plant material. Singh et al. (2016a) reported that epigeic species that live on the upper surface of soil are more prone to physical dispersal forces such as flooding and wind than deep burrowing anecic species. Earthworms feeding on soil surface are most exposed to pesticides and other agrochemicals. Epigeic seems to disperse most actively through the soil and anecic least because of deep vertical burrows. Intensive agriculture is often criticized for negative impacts on environment and human health. This issue may be solved by a better management of organisms living in crop fields. Direct drilling increases

earthworm abundance and species diversity but the beneficial effect of reducing tillage depends on the species present and tillage intensity. Organic amendments enhance earthworm abundance. Earthworms have positive affect on many ecosystem services such pedogenesis, development of soil structure, water regulation, nutrient cycling, primary production, climate regulation, pollution remediation, and cultural services (Blouin et al., 2013). They are also delicacy for some people such as for Ye' Kuana Amerindeans in Venezuela, who eat the raw and smoked earthworms (Paoletti et al, 2003).

7 Earthworm and Bioremediation

The role of earthworms and vermicompost has been worked to bioremediate the pesticide and herbicide content in the soil thus elevating the overall quality of the soil. More than 80% removal of herbicides chlorpyrifos-ethyl, lambda-cyhalothrin, folpet, metaxyl, and myclobutanil was observed in the presence of earthworms and vermicompost can be used as a low-cost natural and reliable material for removal of pesticides and herbicides (Delgado-Moreno and Peña, 2008; Fernández-Gómez et al., 2011). It has also been reported that earthworms play a vital role in bioaccumulation of poly-aromatic hydrocarbons (PAHs) (Jing et al., 2013).

Although the application of pesticides and insecticides increased the crop yield, it also shows negative effect on earthworms present in the soil. Earthworms help in continuous mixing of soil and maintain aerobic conditions that favor degradation of contaminants. The prospects of vermicomposting in bioremediation of soil may help in promotion of agricultural sustainability (Wen et al., 2004). Earthworms not only facilitate the microbial and biochemical soil activity on the substrate but also partially stabilize the earthworm's excretions reducing environmental risks (Coutiño-González et al., 2010).

8 Synergistic Role of Earthworms and Microorganism in Vermicomposting

Earthworms have the ability to eat and mix large amount of soil and organic matter and deposit it in the form of casts. They also enhance incorporation and decomposition of organic matter, increase soil aggregate stability, improve porosity and water infiltration, and increase microbial activity. The earthworm

activity is important for the initial breakdown of plant and animal residues before the organic matter is recycled by the soil microflora. Earthworms are important ecological contributors to the cycling and release of detritus-bound nutrients and act as ameliorators of physical properties of the soil. Cooperating with microbes, earthworms can accelerate the decomposition of organic matter, enhance circulation of carbon, nitrogen, and phosphorus and soil fertility (Hameed et al., 1994). In particular, protozoa and fungi are assumed to form a substantial part of their diet. Earthworms gain weight when reared in cultures of certain fungal species because of the chitin present in cell walls that contains high natural protein and amino polysaccharide. The combined use of earthworms and cellulolytic microorganisms results in more decomposition of kitchen waste than inoculation of earthworms or cellulolytic microorganisms alone (Das and Talukdar, 2001). Aira et al. (2006) evaluated the role of *Eudrilus eugeniae* in cellulose decomposition, by conducting an experiment on pig slurry with microbial rich substrate in small-scale vermireactors with and without earthworms. The presence of earthworms in vermireactors increased significantly the rate of cellulose decomposition (0.43% and 0.26% cellulose loss per day, with and without earthworms, respectively). However, the direct contribution of *Eudrilus eugeniae* to degradation of cellulose was not significant, although its presence increased microbial biomass and enzyme activity (cellulase and beta-glucosidase). The activity of *Eudrilus eugeniae* triggered fungal growth during vermicomposting which led to more intense and efficient cellulolysis. The presence of fungi during vermicomposting process is an additional supplement to the earthworms that contributed to the increased number and weight of the earthworms.

Microbial activities rise in the gut of earthworm because the gut contains easily metabolizable compounds that provide favorable physicochemical conditions for bacterial growth. Bacterial population in earthworm casts is often much higher than the surrounding soil; therefore it promotes the release of available nutrients (Aira et al., 2007; Vivas et al., 2009). On the other hand, there are reports claiming that compost exhibited higher culturable bacterial biomass and metabolic diversity than vermicompost (Atiyeh et al., 2000; Vaz-Moreira et al., 2008). The interaction between bacteria and earthworms may only be mutually beneficial for some types of bacteria. A broad survey of the microbial diversity through the earthworm digestive process found that the abundance of bacteria belonging to *δ-proteobacteria* and *Cytophaga flavobacterium* group increased following digestion,

while the abundance of α , β , and γ -*proteobacteria* decreased. More recent studies have revealed that *Rhizobiales* species (an order nested within the α -*proteobacteria*) are highly involved in the production of N_2O gas from earthworm guts. The anaerobic nature and relatively high availability of nutrients of the earthworm gut stimulates the microbial process of N_2O production via denitrification.

9 Environmental Factors Affecting Earthworm's Population

9.1 pH

Earthworms are very sensitive to pH and it effects the distribution, number, and species of earthworms. The average pH range for earthworms should be 4–8 (Jansirani et al., 2012) but earthworms prefer to be live in soil with pH of 7.0. However, earthworms avoid acid soils of pH <4.5, and prolonged exposure to such soils could have lethal effects (Edwards and Bohlen, 1996). The burrowing speed of earthworms would be faster in neutral pH soil as compared to acidic soil.

9.2 Temperature

The activity, growth, metabolism, respiration, and reproduction of earthworm are generally influenced by temperature. The average temperature required for activity of earthworm is 25–35°C but this temperature range can vary from species to species. The optimum temperature for *Eisenia fetida* was 25°C, and its temperature tolerance was between 0°C and 35°C. Satchell (1967) reported that nights were the most suitable condition for earthworms activity because soil temperature lies in average temperature range. Temperatures below 10°C generally result in reduced or little feeding activity; below 4°C, cocoon production and development of young earthworms cease completely (Edwards and Bohlen, 1996). In extreme temperature conditions, earthworms tend to hibernate and migrate to deeper layers of the windrow or soil for protection. After conducting a series of experiments, Reinecke and Viljoen (1992) concluded that *Eisenia fetida* could survive well even in harsh environmental conditions, especially temperature (5–43°C).

and fluctuating moisture conditions. However, growth and maturation of earthworms was best at 20°C and 85% moisture content under laboratory conditions. [Edwards et al. \(1998\)](#) studied the life cycle of *Perionyx excavatus* and reported that increasing temperatures up to 30°C accelerated the growth of earthworms and lessened the time to sexual maturity. However, the highest rates of reproduction occurred at 25°C both in cattle solids and in sewage sludge. The mean time for egg hatching decreased and the degree of hatching success increased with increasing temperature and was best at 30°C. In [Domínguez et al., 2001](#), made an observation on the biology and population dynamics of *Eudrilus eugeniae* in cattle waste solids and found that earthworm biomass production was temperature dependent and the maximum production being attained temperature of 30°C. The reproductive biology of seven Indian species of earthworm, viz. *Perionyx excavatus* Perrier, *Lampito mauritii* Kinberg, *Polypheretima elongata* (Perrier), *Polypheretima corethrurus* (Muller), *Eutyphoeus gammiei* (Beddard), *Dichogaster modiglianii* (Rosa), and *Drawida nepalensis* Michaelsen was studied in different seasons (natural variation in temperature) by [Bhattacharjee and Chadhuri \(2011\)](#). The peregrine earthworms such as *Perionyx excavatus*, *Polypheretima corethrurus*, *Dichogaster modiglianii*, and *Polypheretima elongata* were continuous breeders with high fecundity. Native *Lampito mauritii* and *Drawida nepalensis* were found to be semicontinuous, whereas, *Eutyphoeus gammiei* was a discrete breeder. Cocoon production decreased or ceased altogether during winter. Temperature also affected the incubation period of cocoons. With increase in temperature within a temperature range of 28–32°C under laboratory conditions, incubation period increased in the endogeic worms (*Polypheretima corethrurus*, *Polypheretima elongata* and *Drawida nepalensis*) and decreased in the epigeic worms (*Perionyx excavatus* and *Dichogaster modiglianii*). There was a significant ($P < 0.05$) positive correlation between number of hatchlings per cocoon and incubation period in *Lampito mauritii* only.

9.3 Moisture

The body weight of earthworms constitutes about 75%–90% of water ([Grant, 1955](#)). So prevention of water loss should be minimum for the survival of earthworms. They cannot survive in dry soil as they loss a plenty of water content from their body.

Dominguez and Edwards (1997) found that 80% moisture was optimum for vermicomposting of pig manure and hostel kitchen waste by *Eisenia anderi*. The average moisture content required for earthworm survival should be between 60% and 90%. Singh et al (2016a) also reported that distribution of earthworms was less in soil having moisture content below 60% but Jansirani et al. (2012) reported that 80% being optimum temperature for earthworms. When surface soil becomes too dry, earthworms start moving to deeper layers of soil to attain optimum moisture content. They also cannot survive in too much moisture content due to which earthworms come out from their burrows during raining and move back after raining.

9.4 Aeration and CO₂

Earthworms obtain oxygen and lose carbon dioxide by the process of diffusion through the body wall. Earthworms are very sensitive to carbon dioxide and in absence or low oxygen, their respiration rate decreases to about 55%–65% (Edwards and Bohlen, 1996). The burrows made by earthworms help to get optimum oxygen required for their survival. The feeding and casting activities of earthworm also reduced if proper oxygen is not supplied to their body (Dominguez, 2004).

9.5 Ammonia

Earthworms are very responsive to ammonia and cannot live in soil that contains high level of ammonia. The level of ammonia should be <1 mg/g for proper earthworm activity (Edwards, 1988). The soil having ammonia more than 1 mg/g is not acceptable by the earthworms. According to Dominguez (2004), for better vermicomposting efficiency, the waste should be free from ammonia that can be done by composting process. According to USDA 2011, ammonia will kill up to 10% of earthworm's population and its activity also becomes reduced.

9.6 Food Supply

Quantity, quality, and placement of food influence earthworm populations. Earthworms eat organic residue that needs to be present in sufficient quantity. The quality of residue is also important. Residue with a high carbon to nitrogen (C:N) ratio is not very palatable for earthworms while the presence of manure

can make it more palatable. Packed manure is an excellent food source for earthworms. In some cases, residue has to undergo some weathering before earthworms are able to digest it. Topsoil dwellers need smaller particles than subsoil dwellers, which can use large leaves. The placement of food becomes a critical issue for some earthworm species. The earthworms grow best in easily metabolizable organic matter and nonassimilated carbohydrates, these also favor their reproduction (Flack and Hartenstein, 1984). Growth and reproduction were found to be correlated positively to the volatilable solid content of the waste (Edward, 1998). Earthworm growth slows down when C:N ratio and temperature is high (Bostrom, 1987). The biomass gain by *Eisenia fetida* was found to depend on population density and food type with particle size that play a significant role in vermicomposting. Viljoen and Reinecke (1989) observed that single raised worm began to gain biomass at a higher rate (after 170 days) than those raised in batches (after 230 days). The population density of worms per unit volume or weight of a waste is very important in determining the rate of earthworm growth and reproduction. While Dominguez et al. (2000) reported a decrease in worm biomass even when additional feed was provided to worms every week.

So the factors relating to the growth of earthworm may be considered in terms of physicochemical and nutrient characteristics of waste along with temperature, pH and moisture content of feedstocks. The organic waste palatability and intensity of feeding by earthworm is directly related to the interaction of these parameters and consequently it affects growth and reproduction of earthworm (Suthar, 2007). In 1979, Hartenstein et al. reported the regression equations for *Eisenia fetida* with respect to age at which 50% of the population became clitellate at 25°C in relation to population density in activated sludge and in horse manure. Data provided age at which reproduction terminated in relation to population density, optimum population density for reproduction, and hatchability.

9.7 Soil Texture

Earthworms prefer soils with loamy texture. Coarse sand can be a negative factor either because the abrasive action of sand grains damages their skin, or because these soils dry out more easily. In some studies, clay soils had fewer earthworms than lighter-textured soils.

10 Sexual Development, Cocoon Production, Hatching Rate, and Hatchlings

Food availability, type of food, population density, and temperature determine the time of sexual maturation in earthworm (Neuhauser et al., 1980). The growth rate of earthworm slows down at higher temperature. The temperature above the optimum for growth decreased the incubation period of earthworm. Biochemical quality of the feed is an important factor in determining the time taken to reach sexual maturity, onset of reproduction and cocoon production (Edward et al., 1998). The most rapid maturation in earthworm was at 25°C and degree of hatching success increased with increasing temperature and it occurred at 17.8 days at 25°C and 15.3 days at 25–37°C (Edwards, 1988). Venter and Reinecke (1988) observed that the first and last cocoon produced by *Eisenia fetida* were less viable than those produced between days 30 and 120 during degradation of waste. Edward (1998) reported that development time of cocoon for temperate epigeic worm was 32–73 days in *Eisenia fetida*, 40–126 days in *Dendrobaena veneta* and for tropical epigeic worms *Eudrilus euginae* and *Perionyx excavatus* it was 13–27 days and 16–21 days. The average incubation period for cocoons of *Eudrilus eugeniae* between 70 and 100 days of age was 16.89 days. The hatching success of the cocoons was 84% in cattle manure, 50% in distilled water, and 48% on moist filter paper.

A positive correlation was observed by Satchell (1967) between number of cocoons and the zone of soil inhabited by worms. The species of the deeper soil layer protected from adverse environmental condition produced few cocoons, whereas those living near the surface and facing adverse condition produced more cocoons. Lavelle (1981) found a positive relationship between the size of the adult and cocoons produced by the earthworms but Senapati and Sahu (1993) reported that the size of worms bore a negative relationship with the number of cocoons. They asserted that greater rate of cocoon production by small-to-medium-sized epigeic earthworm *Dichogaster modiglianii* and *Perionyx excavatus* and top soil endogeic worms *Polypheretima corethrurus* and *Lampito mauritii* was due to exposure to the high mortality risk environment. Lee (1985) and Edwards and Bohlen (1996) proposed that cocoon size was not always correlated with worm size as cocoon production and time for maturation of cocoon varied with species, population density, and external factors especially soil temperature, moisture, and energy content of the available food and age of worms.

11 Earthworm Cast

Earthworm is an important component for the development and maintenance of physicochemical properties of soil by converting biodegradable materials and organic wastes into nutrient-rich product, which emerge from their burrows to deposit the fecal matter (vermicast) on the surface (Singh et al., 2016b). The castings egested by earthworm have generally been assumed to be more stable than the parent soil aggregates and contain certain hormones, enzymes, microorganisms, inorganic, and organic materials which it acquires during the passage of soil through the earthworm gut (Tersic and Gosar, 2012). Jouquet et al. (2008a) reported that cast of earthworm shows greater stability, higher pH, and moisture. It is richer in C, N, Ca, Mg, K, and polysaccharides than the surrounding soil and hence it is a hotspot for microbial activity.

The physicochemical properties of the cast depend on the ingested soil material, on the life trails of earthworm that produced them and probably on the interaction between both. The vermicast produced by the earthworm is a good source of nutrients for plants as compared with compost and synthetic fertilizers. Earthworm cast contained mixture of inorganic and organic materials from the soil that are negated after passing through earthworm intestine.

In addition to it, earthworm cast also increased plant dry weight, plant nitrogen uptake, and provides a better root growth medium by improving soil porosity (Chaoui et al., 2003). The characteristics of the soil that they ingest are likely to be a primary factor influencing the chemical, physical, and biological properties of egested cast (Jouquet et al., 2008b; Shipitalo and Protz, 1989). Cast produced by different earthworm species present different chemical and physical properties if earthworms do not belong to same ecological group (Zhang and Schradel, 1993). Different earthworm species are also known to impact differently the communities of microorganisms found in their cast. Schradel and Zhang (1997) reported that casts had higher organic carbon content than the bulk soil, especially in loam soil compared with clay soil. Norgrove and Hanser (2000) also suggested that the food selectivity by earthworm might enable them to adjust their feeding regime to nutrient pool soil. They reported a negative correlation between the matter and organic carbon concentration in casts and in surrounding soil. Jana et al. (2010) showed how *Aporrectodea caliginosa* produces nutrient-rich casts in a poor soil and allows plants growing in a nutrient poor soil to grow well. Multivariate analysis showed that a difference of soil type had a

major impact on cast properties (62%) compared to the impact of a difference of earthworm species ([Clause et al., 2014](#)).

12 Role of Humic Acid in Vermicast

Humic substances are heterogeneous mixtures of naturally occurring molecules that are present in all soils, water, and sediments. Humic substances are primarily the microbiological transformation products of lignin and other plant detritus. They cannot be classified as any other chemical class of compounds and are traditionally defined according to their solubility. Humic acids (HAs) are insoluble at acidic pH values ($\text{pH} > 2$) and soluble at higher pH values, while fulvic acids (FA) are soluble in water at all pH values. From an environmental point of view HA and FA are particularly interesting because in their molecular structures there are both polar and nonpolar substituent's; therefore, they can interact both with water soluble and insoluble compounds ([McCarthy, 1989](#)). Humic compounds are produced by abiogenic chemical reaction, including condensation, polymerization, oxidations, and reductions, by which relatively low-molecular weight compounds such as degradation products of biopolymers (i.e., proteins and carbohydrates) are linked to one another ([Rashid, 1974](#)). FA is generally more aliphatic and less aromatic than HA and is richer in carboxylic, phenolic, and ketonic groups.

12.1 Effect of HAs Derived From Vermicompost on Plant Growth

It is well established that earthworms have beneficial physical, biological, and chemical effects on soils and many researchers have demonstrated that these effects can increase plant growth and crop yield in both natural and managed ecosystems ([Edwards and Bohlen, 1996](#); [Edwards, 1998](#)). These beneficial effects have been attributed to improvements in soil properties and structures, to greater availability of mineral nutrients to plants and to increased microbial populations and biologically active metabolites such as PGR ([Tomati et al., 1988](#); [Doubé et al., 1997](#)).

The earthworms fragment the organic waste substrates, stimulate microbial activity greatly, and increase the rate of mineralization, rapidly converting the wastes into humus-like substances with a finer structure than composts ([Elvira et al., 1996](#)). The effects of HA on the growth of a variety of crops including cereals and legumes, vegetables, ornamental, and flowering

plants have been easy to read in the green-house and to lesser degree in field crops ([Chen and Aviad, 1990](#)). These investigations have demonstrated consistently that HA in vermicompost have beneficial effects on plant growth. The vermicomposts have consistently improved seed germination, enhanced seedling growth and development, and increased plant productivity.

When HAs derived from pig manure vermicompost were mixed in different ratios in MM360 (Metro Mix 360) medium to grow tomato seedlings, and humates extracted from pig manure and food waste vermicomposts were mixed with vermiculite to grow cucumber seedlings, there was a significant increase in the growth and yield of tomato and cucumber seedlings. List of parameters of various plants enhanced by applying HAs extracted from vermicompost are given in [Table 3](#).

It was observed that effect of HAs on plant growth depended on their applied concentrations, plant species, nature of container medium, and source of vermicompost. Authors attributed the

Table 3 List of Parameters of Various Plants Enhance by Applying Humic Acids Extracted From Vermicompost

S. No	Crop/Plant	Parameters Enhanced	References
1.	Wheat (<i>Triticum aestivum</i> L.)	Rapid plant growth, improve Zn and Cu bioavailability	Mackowiak et al. (2001)
2.	Tomato (<i>Lycopersicum esculentum</i> L.) and cucumber	Plant height, leaf area, root dry weight, shoot dry weight	Atiyeh et al. (2002)
3.	Potato (<i>Solanum tuberosum</i>)	Increased yield by 18 cwt/acre	Hopkins and Stark (2003)
4.	Tomatoes, marigold, pepper, and strawberry	Plant heights, leaf areas, shoot dry weights, root dry weights, number of fruits	Arancon et al. (2004)
5.	Gerbera	Increased root growth, high level of micro and macronutrient	Can et al. (2008)
6.	Corn	Increased dry weight, increase nitrogen, potassium, and phosphorus uptake	Khaled and Fawy (2011)
7.	Basil (<i>Ocimum basilicum</i> L.)	Wet and dry yield, essence yield, chlorophyll content	Befrozfar et al. (2013)
8.	<i>Impatiens walleriana</i> L.	Plant height and diameter, dry root and shoot weight, high flower number	Esringu et al. (2015)

increase in growth to hormone-like activity of vermicomposts (Atiyeh et al., 2002). In another study, HAs were extracted from cattle, food, and paper-waste vermicomposts substituted in soil-less growth medium, Metro-Mix 360 (MM360) increased growth and yields of marigold, peppers, and strawberry plants. Parameters such as plant heights, leaf areas, shoot dry weights, and root dry weights increased in all the three crops. A field study was conducted by Befrozfar et al. (2013) to evaluate the effect of vermicompost, plant growth-promoting bacteria and HA on growth and essence of basil. HAs were applied as foliar spray and seed treatment. Highest yield, plant height, and essence percentage was recorded in combined treatments of HAs with plant growth-promoting bacteria. Authors suggested that treatments of HAs, plant growth-promoting bacteria and vermicomposts can be used for a sustainable agriculture discouraging the use of chemical fertilizers.

The greatest plant growth responses and yields have occurred usually when vermicomposts substituted in growth media as smaller proportions (Subler et al., 1998). Atiyeh et al. (2002) speculates that the growth responses by addition of vermicompost that appear like “hormone induces activity” may be associated with the high level of HAs in vermicompost.

12.2 Effect of HA on Soil Microbial Populations

The various groups of the soil microbial community reacted differently to the amendments of potassium humates. Total aerobic bacteria were stimulated by CdHA (cadmium humic acid complex) given at higher rates (4000–8000 mg/kg) from the earliest sampling. The bacterial growth in the soil progressively increased up to 2000 mg/kg of humates. After 120 days, differences in bacterial counts became negligible. Pots treated with KCL did not show any significant increase in bacterial counts in comparison with the soil previously wetted. Hoagland solution (nutrient solution for plants growth) significantly affected total aerobic bacteria at 1000 and 2000 mg/kg up to 60 days but not thereafter. The increase in bacterial biomass from humates may be related to the availability of carbonaceous substrates for heterotrophic growth. Furthermore, the combination of Hoagland's solution and humates would improve bacterial degradation and use of humified substances by rendering their C/N ratio more favorable for microbial growth. Positive effects on the growth of total aerobic bacteria were also observed in pots amended with Tween 80 alone or in

combination with Hoagland's solution. However, bacterial counts only increased with Tween 80 at 1000 mg/kg or greater, and the increase lasted for 90 and 60 days for Tween 80 and Tween 80 + Hoagland's solution, respectively. Again, these results suggest the involvement of membrane mechanisms enhancing a higher permeability to nutrients (Vallini et al., 1993).

Although humates may contribute to microbial growth by rendering available small carbonaceous fragments, surprisingly microbes with possible degrading capabilities towards HA did not clearly benefit from the addition of CDHA to the soil. However, neutralization of HA proceeds rather slowly and takes longer than the experimental period used here. With respect to soil actinomycetes and cellulolytic microorganisms, the present study confirms previous observations of Vallini et al. (1993) and Valdrighi et al. (1996) that HA exert only a weak stimulative effect of these groups of microorganisms. Even CDHA added to the soil in combination with Hoagland's solution produced a similar response. On the other hand, Tween 80 alone or in combination with Hoagland's solution did not affect either actinomycetes or cellulolytic microbes. None of the treatments or treatment combinations had any significant effects on counts of filamentous fungi.

Further, as pointed out elsewhere (Valdrighi et al., 1996), HAS stimulate growth of autotrophic nitrifying bacteria, especially the nitrite oxidizing ones, at the higher conc. (1000–8000 mg/kg) of CDHA supplied to the soil. This beneficial effect was already detectable after 7 days from the start of treatment. The addition of Hoagland's solution amended with humates gave analogous results. Also, Tween 80 alone or in combination with Hoagland's solution visibly increased the growth of nitrifying bacteria. Autotrophic nitrifiers probably take advantage of the presence of humic substances at either the physiological or biochemical levels (Visser, 1985). Similar responses to humic products and surfactants such as Tween 80 suggests that CDHA affected the nitrifiers through improved cell permeability with biological membranes being one of the prime targets of such surface active agents (Tan and Lopez-Falcon, 1987).

13 Effect of Vermicompost on Plant Growth

The effect of vermicompost on different plant species is given in Table 4.

Table 4 Effect of Vermicompost and Vermiwash on Different Plant Species

S. No	Plants	Important Findings	References
1	Tomato	(I) Vermicompost (VM) increased the yield by 16.3%, 9.6%, 52.0%, and 69.3%, and the vitamin C content by 8.2%, 59.2%, 15.2%, and 80.3% when compared with chick compost (CM), horse compost (HM), chemical fertilizer (CF), and no fertilizer (CK), respectively. (II) VM also decreased the soluble solids and total acidity than that in CM, HM, CF, and CK, respectively. (III) VM increased acid phosphatase, catalase, and urease activities in soil as compared with the other treatments. (IV) The results concluded that the VM increased tomato yield under 60%–70% of field capacity and the effects of vermicompost on soil fertility varied with soil water regime	Yang et al. (2015)
2	Maize	(I) Plants fertilized with vermicompost enriched with rock powder were taller than plants fertilized with nonenriched vermicompost. (II) Vermicompost enriched with steatite powder resulted in a larger effect on growth of plant than applying vermicompost of none-nriched manure and steatite alone to the soil. (III) Results revealed that 20% of gneiss and steatite powders could be added to manure to be vermicomposted	De Souza et al. (2013)
3	<i>Capsicum frutescens</i>	(I) Liquid biofertilizer vermiwash was obtained by biodegradation of jackfruit waste (<i>Artocarpus heterophyllus</i>) by earthworm <i>Eudrilus eugeniae</i>. (II) Treatment with vermiwash in <i>Capsicum frutescens</i> showed increased root and shoot length as well as number of leaves than the untreated plant. (III) The results suggest that the quality liquid manure vermiwash is an effective biofertilizer which facilitate the increased uptake of nutrients by the plants resulting in higher yield/growth and also improves soil health	Varghese and Prabha (2014)
4	<i>Casuarina</i> and <i>Jatropha</i> seedlings	(I) Nursery experiments were carried out to find the effect of vermicompost on casuarina and Jatropha seedlings. (II) Seeds of 1-month old seedlings of casuarina and jatropha were planted in the polybags with various treatment groups. (III) The growth of casuarina seedlings was equally promoted by all kinds of vermicompost. Coffee pulp vermicompost application registered the highest collar diameter for jatropha seedlings followed by pungam vermicompost	Kiruba et al. (2013)

Table 4 Effect of Vermicompost and Vermiwash on Different Plant Species—Cont'd

S. No	Plants	Important Findings	References
5	Tomato seedlings (<i>Lycopersicum esculentum</i> cv. Momotaro)	(I) The results revealed that the vermicompost with animal origin treatment had the highest values of tomato seedling height, stem diameter, number of leaves per seedling, and total dry matter, followed by other treatments (vermicompost with vegetable origin, cotton composting). (II) The higher growth in the vermicompost with animal origin treatment may be due to the higher mineral element content	Tejada and Benitez (2015)
6	<i>Allium cepa</i> L.	(I) The study showed higher plant growth in the combined treatment of vermicompost and NPK, as measured by the vegetative growth of bulbs, number and length of tillers per bulb, fresh weight of bulbs and by the biochemical characteristics of the onion tillers/leaves (total chlorophyll, carotenoids, protein, and total sugar contents). (II) Comparison of the mixed treatment as compared with the control showed increases in bulb size (54%), total number of bulbs per bed (52%), and fresh weight of all bulbs (198%). (III) The study concluded that application of a combination of mineral fertilizer and vermicompost in the field can influence positively the biological properties and fertility of soils, and support better plant growth and this combined application can reduce the quantity and cost of mineral-fertilizers application for bulbous-crop cultivation by 50%, while also sustaining soil biological activity of tropical and subtropical soils	Srivastava et al. (2012)
7	<i>Catharanthus roseus</i> L.	(I) The results revealed that the vermicompost-treated plants had a higher plant height, leaf area, collar diameter, number of main stems, number of nodes and leaf dry weight. Severe defoliation (50%) reduced most above traits in comparison with those of the controls. (II) Plant fresh and dry weights were the only parameters that were influenced by the interaction of mycorrhizal and vermicompost treatments in which the highest fresh and dry weights were observed in the undefoliated plants that were treated with vermicompost. (III) None of the treatments affected total leaf alkaloid. The mycorrhizal-treated plants displayed a root colonization of 72%, compared with 5% for the control plants	Tabrizi et al. (2016)

Continued

Table 4 Effect of Vermicompost and Vermiwash on Different Plant Species—Cont'd

S. No	Plants	Important Findings	References
8	Chickpea (<i>Cicer arietinum</i> L.)	(I) The results showed that the vermicompost treatment under no-stress conditions significantly increased total chlorophyll content [Chl (<i>a</i>+<i>b</i>)], intercellular CO₂ concentration (<i>C_i</i>), net photosynthetic rate (<i>P_N</i>), transpiration rate (<i>E</i>), and maximal quantum yield of PSII photochemistry (<i>F_v/F_m</i>) at all three stages. (II) The 10% and 20% addition of vermicompost enhanced significantly the Chl content and <i>F_v/F_m</i> under moderate drought and <i>F_v/F_m</i>, <i>C_i</i>, and <i>P_N</i> under severe drought at the flowering stage. (III) The authors concluded that the study showed a positive effect of the vermicompost fertilizer on photosynthesis of chickpea under no-stress conditions and was not found under moderate drought and severe drought conditions	Hosseinzadeh et al. (2016)
9	Cluster bean (<i>Cyamopsis tetragonoloba</i>)	(I) The study observed that up to 51.5% greater germination success occurred in the vermicompost treatments compared with controls. (II) Vermicompost also supported better plant growth in terms of stem diameter, shoot length, shoot mass, number of leaves, and leaf pigments. (III) Vermicompost application enhanced root nodule formation, reduced disease incidence, and allowed for a smaller number of stunted plants. (IV) The results indicated that lantana vermicompost has the potential to support germination, growth, and fruit yield better than equivalent quantities of inorganic fertilizers	Karthikeyan et al. (2014)
10	Rosemary (<i>Rosmarinus officinalis</i> L.)	(I) The study showed that among the various treatments, the application of vermicompost (8 t ha⁻¹)+fertilizer nitrogen (N) phosphorus (P) – potassium (K) (150:25:25 kg ha⁻¹) produced optimum herbage and oil yield of rosemary compared with control (no fertilizer) and was found to be on par with application of fertilizer NPK 300:50:50 kg ha⁻¹. (II) Content and quality of oil were not influenced by vermicompost and chemical fertilizers and it was observed that available N and P were greater in postharvest soils that received vermicompost alone or in combination with inorganic fertilizers than control (no fertilizer) and inorganic fertilizer-treated soil. (III) The results indicated that combined application of vermicompost and chemical fertilizer helps to increase crop productivity and sustain the soil fertility	Singh and Wasnik (2013)

Table 4 Effect of Vermicompost and Vermiwash on Different Plant Species—Cont'd

S. No	Plants	Important Findings	References
11	Chilli crop (<i>Capsicum annuum</i> L)	(I) The results revealed that the vermicompost organic fertilizer increased the pore space, water-holding capacity, cation-exchange capacity, organic carbon, other micro-macro nutrients—Ca, Mg, Na, Fe, Mn, Zn, Cu, and microbial population. (II) The study showed that the effect of organics on growth, yield parameters of chilli of FYM @ (12.5 t/ha)+vermicompost @ (2.5 t/ha) showed better results compared to other treatments	Kumar et al. (2016)

13.1 Seed Germination

The application of vermicompost based on macrophyte is reported to be a beneficial for *Solanum melongena* (brinjal) and a significant higher rate of germination was recorded (Najar et al., 2015). An increase in seed germination of *Rumex obtusifolius* and *Pinus pinaster* by 48% and 16%, respectively, with the application of cattle manure and rabbit manure vermicompost, respectively, was reported by Zaller (2007) and Lazcano et al. (2010). Similar observations have been reported in green gram, *Phaseolus aureus* (Karmegam et al., 1999) and tomato, *Lycopersicum esculentum* (Atiyeh et al., 2000; Najar and Khan, 2013).

13.2 Plant Growth Parameters

Plant growth parameters that include plant length, root length, dry weight, number of leaves, area, and dry weight of leaves have been analyzed in many studies. Bachman and Metzger (2008) reported an enhanced shoot and root weight, leaf area, and shoot-root ratio in tomato and French marigold. A significant increase in shoot length, root length, leaf area, and plant biomass of *Lycopersicum esculentum* with the application of vermicompost was also recorded by Najar and Khan (2013). The addition of vermicompost as a constituent of growing substrates is beneficial for growth of tomato (Surrage et al., 2010). Almost all the growth, yield, and quality parameters such as mean diameter of stem,

mean height of plant, yield/plant, marketable yield/plant, mean leaf number, and total plant biomass increased significantly in vermicompost medium as compared with control in case of tomato, *Lycopersicum esculentum* L. as reported by Joshi and Vig (2010). It is also known to stimulate growth of various species of plants including horticultural crops.

13.3 Yield Parameters

A number of studies depict better production of fruits/clusters and large-sized fruits with higher total yield when compared with the control. An increase in tomato fruit yield with the amendment of 10%–20% vermicompost was reported by Atiyeh et al. (2000). Arancon et al. (2006) also reported an improvement in growth and yield of strawberries with vermicompost application. Increase in yield of wheat in cattle dung-based vermicompost-amended soil has been reported by Joshi et al. (2013).

13.4 Mitigation of Plant Diseases and Pathogens

Vermicompost helps in mitigation of plant diseases and suppression of plant pathogens (Trillas et al., 2006). Plots of strawberry amended with 7.5 t/ha vegetable waste-based vermicompost over the control were found to show a decreased occurrence of physiological disorders such as gray mold (2.7%), fruit malformation (4.1%), albinism (4.6%), and increased marketable fruit yield (58.6%) as reported by Singh et al. (2008). According to Chandrakumar et al. (2009), application of vermicompost led to decline in infection of *Leucinodes orbonalis* on *Solanum melongena*. In regard to fungal diseases, the addition of vermicompost extracts to three ornamental plants significantly reduced sporulation of the pathogen *Phytophthora cryptogea* (Orlikowski, 1999). Infection caused by *Fusarium lycopersici* (Szczzech, 1999) and *Phytophthora nicotianae* (Szczzech and Smolinska, 2001) was significantly reduced with the addition of solid vermicompost to tomato seeds. Singhai et al. (2011) also established a significant suppression of common scab of potato through application of vermicompost. The addition of organic amendment has been noted to suppress plant diseases effectively as soils with low organic matter are conducive to plant root diseases. Rostami et al. (2014) also reported that vermicompost have a remarkable potential as control agents against root-knot nematode and in improvement of host plant health.

13.5 Decrease in Pest Population

A study showed that vermicompost amendment led to statistically significant decrease in arthropods (aphids, buds, mealy bug, and spider mite) populations and subsequent reduction in plant damage (Edwards and Arancon 2004; Edwards et al., 2010). A radical suppression of spotted spider mites (*Tetranychus* sp.) and aphid (*Myzus persicae*) in *Lycopersicum esculentum* plants postvermicompost application. Munroe (2007) reported the presence of chitinase enzyme in vermicompost, which breaks down the chitin in the exoskeleton of insects and thus repels many different insect pests. Population of two species of beetles in soil (*Acalymma vittatum*, *Diabotrica undecimpunctata*) was reduced significantly with vermicomposting in comparison to organic fertilizers (Arancon et al., 2005). Addition of food waste vermicompost to several vegetable crops (tomatoes, cucumber, cabbage, bush beans, and eggplants) led to a significant reduction in the populations of spider mites (*Tetranychus urticae*), mealy bugs (*Pseudococcus* sp.), and aphids (*Myzus persicae*) (Arancon et al., 2007). The larvae of the worm *Manduca quinquemaculata* decreased in number after addition of vermicompost to a cucumber crop (Yardim et al., 2006).

13.6 Increase in Plant Nutrients

Nutrients in the vermicompost are in a form that is readily available to plants due to chemical and microbial digestion in the gut of earthworm. Vermicompost enhances soil biodiversity by promoting the beneficial microbes which in turn enhances the quality of plants. Another study reported an increase in the ecological microbial biodiversity (esp. MBCU1 (*Pseudomonas stutzeri*) and MBCU3 (*Pseudomonas mosselii*)) after vermicompost application and also showed a significant enhancement in vegetative growth parameters in chickpea and groundnut seedling. This increase may be because of the congenial condition for the growth of microbes in the digestive tract of earthworms and due to the nutrient-rich organic waste that forms the substrate for growth of microorganisms and provides them energy (Pandya et al., 2014). Vermicompost also helps in initial rapid and subsequently slower release of phosphorus thus generating a fast initial and then prolonged fertilizing effect (Espinoza et al., 2014). The use of vermicompost leachate is also described to alleviate deficiency of phosphorus and potassium in tomato seedlings and thus could easily serve as a substitute for the same in growth of tomatoes (Arthur et al., 2012).

13.7 Increase in PGR

Biologically active metabolites such as PGR have been discovered in vermicompost/vermicast materials (Atiyeh et al., 2002; Canellas et al., 2002). Various studies reported a quantitative evidence of Cytokinins, Indole acetic acid, 18 Gibberlins and 6 Brassinosteroids, which contribute to various physiological responses such as growth and yield and improved stress responses to biotic and abiotic stresses observed in vermicompost-treated plants. Some earthworm species can excrete auxin-like substances at the rate of 40 ng per day per individual worm. Growth-regulating substances with gibberellin, cytokinins, and auxin activity are reported to be present in earthworm casts in microgram per gram concentration (Tomati et al., 1988). Neilson (1965) has also reported that earthworms secrete growth-promoting hormone auxins, cytokinins, and flowering hormone gibberellins as evidences by studies on vermicompost. It was demonstrated by Grappelli et al. (1987) and Tomati et al. (1988) that the addition of aqueous extracts from vermicompost showed similar growth patterns as with the addition of auxins, gibberellins, and cytokinins through the soil in ornamental plants. Neilson (1965) reported the first evidence of the presence of indole compounds in the tissues of *Aporrectodea caliginosa*, *Lumbricus rubellus*, and *Eisenia fetida*.

13.8 Increasing Biological Resistance

Vermicompost have the capability to induce biological resistance in plants as it contains some antibiotics and actinomycetes. Pesticide spray was significantly reduced where earthworms and vermicompost applied in agriculture (Suhane, 2007).

13.9 Improving Forage Quality

Precomposting followed by vermicomposting provides an effective way of ruminant manure management. Further, the vermicompost produced can be used as a good fertilizer and also has potential of being feed supplement to ruminant. Precomposting of ruminant manure and its subsequent vermicomposting reduces the environmental pollution from ruminant production and provide a potential of feed supplement to ruminants (Nasiru et al., 2013).

14 Anthropogenic Activities and Its Effect on Earthworm

Soil and crop management practices can influence many soil properties that affect earthworms. Some practices can have immediate effects on earthworms, whereas others may gradually change earthworm population and activities over several years. So when you are considering management options, you should also think about their effects on earthworms.

14.1 Tillage

Soil tillage greatly affects earthworms. The burial of crop residue and manure by tillage favors topsoil dwellers over subsoil dwellers. In long-term clean-tilled fields, night crawlers are scarce. Tillage also stimulates drying the surface soil and wide day/night temperature fluctuations. With this, number of earthworms is less in clean-tilled fields as compared with no-tilled fields. Tillage brings earthworms to the surface where they are subject to predators such as birds. Total earthworm populations in long-term no-tilled fields are typically at least twice those of clean-tilled fields ([Capowiez et al., 2009](#); [Crittenden et al., 2014](#)).

14.2 Crop Rotation

Providing earthworms with a diverse diet is important. Crop residue of leguminous species (low C:N ratio) is more palatable to earthworms than that of mature grass and grain species (high C:N ratio). However, a legume such as soybean produces very little crop residue, which limits the quantity of food available to earthworms. Earthworms thrive in grasslands and alfalfa. In one grassland study, 70 earthworms were counted per square foot (more than 3 million earthworms per acre) ([Edwards and Bohlen, 1996](#)).

14.3 Fertilizer and Lime

There is good evidence that most inorganic fertilizers favor the build-up of large numbers of earthworms, probably due to the increased amounts of crop residues being returned to the soil. Anhydrous ammonia and ammonium sulfate have been found to have negative effects on earthworms. This may be due to the acidifying effect of this fertilizer, but also due to the toxic effect

of ammonia. Liming to neutralize acidity stimulates earthworm activity ([Singh et al., 2016a](#)).

14.4 Pesticides

The effects of pesticides on earthworms depend on the type of pesticide and its rate of application, earthworm species and age, and environmental conditions. Most inorganic chemicals tested are no longer in use as pesticides. Based on the limited amount of information available, these chemicals do not seem to be very toxic to earthworms, except when they accumulate in soil over a long period of time ([Edwards and Bohlen, 1996](#)). Pesticide health risks to earthworms depend not only on the toxicity of the chemical but also on the exposure to it. On the other hand, earthworms that crawl on the soil surface (such as night crawlers) have a higher exposure to surface applied pesticides than those feeding and burrowing below the soil surface ([Singh et al., 2016a](#)). On the other hand, pesticides injected in a small slot in the soil (such as the seed slot) may not come in contact with many earthworms and therefore will not pose a significant threat for the population at large ([Datta et al., 2016](#)).

15 Earthworms Effect on Soil

They maintain the physicochemical properties of soil by converting biodegradable materials and organic wastes into nutrient-rich product.

15.1 Improve Nutrient Availability

Worms feed on plant debris (dead roots, leaves, grasses, manure) and soil. Their digestive system concentrates the organic and mineral constituents in the food they eat, so their casts are richer in available nutrients than the soil around them. Nitrogen in the casts is readily available to plants. Worm bodies decompose rapidly, further contributing to the nitrogen content of soil. It is reported that worm casts release four times more phosphorus than surface soil. Worms often leave their nutrient-rich casts in their tunnels, providing a favorable environment for plant root growth. The tunnels also allow roots to penetrate deeper into the soil, where they can reach extra moisture and nutrients. Earthworm tunneling can help incorporate surface applied lime and fertilizer into the soil.

15.2 Earthworm Increases Soil Macroporosity and Water Infiltration

The extensive channeling and burrowing by earthworms loosens and aerates the soil and improves soil drainage. Soils with earthworms drain up to 10 times faster than soils without earthworms. In zero-till soils, where worm populations are high, water infiltration can be up to six times greater than in cultivated soils. Earthworm tunnels also act, under the influence of rain, irrigation, and gravity, as passageways for lime and other material. Earthworm affect soil mechanical and hydraulic properties through their burrowing activities which generate macropores that significantly impact water infiltration and thus are important for supplying crops with water as well as controlling surface run off and erosion (Le Bayon et al., 2002). Pore morphology varies depending on the earthworm ecological group.

- (a) Anecic earthworm dig large, vertically oriented galleries that extend to depth greater than in the soil profile.
- (b) Endogeic earthworms' burrows are not preferentially oriented in the vertical direction and the burrow diameter is smaller than anecic and is not so deep.
- (c) Epigeic earthworms remain in litter layer and in the first few centimeters of the soil and thus have little effect on the soil macroporosity.

Ernst et al. (2008) showed that earthworm's ecological group affects soil water characteristics. The anecic and endogeic enhanced drying in the 0- to 1-cm soil layer by increasing soil aeration and subsequently evaporation through their burrows. In contrast, epigeic tended to favor water storage in the top soil. Earthworms burrows affect water availability to crops. Rice growing in a green house in the presence of endogeic worm *Reginaldia omodeoi* had a positive effect on the plant growth in a well-watered treatment but a negative effect in a water deficient treatment (Blouin et al., 2007). Clements et al. (1991) showed that in a Mediterranean soil, water percolation was found to be correlated positively with earthworm biomass, burrows length, and burrow surface. The infiltration rate increased by 150 mm/h per 100 g/m² of earthworms. This correlation was even stronger when only anecic species were considered. Water infiltration through earthworm burrows can be a source of crop water or percolate through the soil profile (Bouche and Al-addan, 1997). Shuster et al. (2002) reported that infiltration of water increase by anecic species of earthworm and reduced soil erosion by 50%. Jouquet et al. (2008b) reported in a field experiment with 40% slope that *Amyntas khami* were responsible for a 75% decrease in runoff.

Endogeic species also increase soil macroporosity and water infiltration, which tends to reduce runoff but [Blanchart et al. \(2004\)](#) reported that some endogeic species also produced small-sized casts, which favor surface sealing and contribute to soil erosion. These contradictions between the results about the impact of earthworm on soil structure, water infiltration, and soil erosion are probably due to the rainfall regime, earthworm abundance, earthworm species, and the amount of organic matter available at soil surface.

15.3 Improve Soil Structure

Earthworm casts convert soil particles into water-stable aggregates. The size, quantity, and stability of soil aggregates reflect a balance between factors such as organic amendments, soil microorganisms, fauna, and disrupting factors as bioturbation and culture ([Six et al., 2002](#)). These are able to store moisture without dispersing. Research has shown that earthworms which leave their casts on the soil surface rebuild topsoil. In favorable conditions they can bring up about 50 t/ha annually, enough to form a layer 5 mm deep. One trial found worms built 18-cm thick topsoil in 30 years ([Lemtiri et al., 2014](#)).

15.4 Improve Productivity

Earthworms introduced to worm-free perennial pastures produced an initial increase of 70%–80% pasture growth. Researchers also found that the most productive pastures in the worm trials had up to 7 million worms per hectare, weighing 2.4 t. [Groenigen et al. \(2014\)](#) reported that the presence of earthworm in agro-ecosystem increases 25% crop yield. Earthworm produce cast, which consist of all nutrient contents required for plants growth ([Bhaduria and Saxena, 2010](#)). There is a close correlation between pasture productivity and total worm weight, with some 170 kg of worms for every tonne of annual dry matter production.

16 Earthworm Enemies

The earthworm has many enemies, including mites, nematodes, fly larvae, birds, rats, mice, rat moles, gophers, frogs, and snakes. Small, brown mites occasionally infest worm beds by the millions. Although live, healthy worms are not harmed, the injured or dead ones are eaten. These mites can become so populated that most of the food is eaten in one night. After wetting the bed, mites swarm to the surface, often covering the entire bed. Red

mites are parasites that suck earthworm blood while they are attached. They also pierce and suck fluid from earthworm egg capsules (Lyon, 1996).

17 Conclusion

Earthworms maintain aerobic condition by continuous mixing of soil and also favor the degradation of contaminants. The prospects of vermicomposting in bioremediation of soil may help in promoting agricultural sustainability. Earthworms not only facilitate the microbial and biochemical soil activity on the substrate but also reduce the environmental risk. Earthworms and its vermicast may work as a driving force in sustainable food production as they improve soil health and fertility, protects crop plants from pests and diseases, increases plant growth parameters, and nutritional quality. Vermitechnology is the only permanent and cheapest solution to overcome the dangerous effects of modern day agriculture.

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EVALUATING THE ENVIRONMENTAL, ECONOMIC, AND SOCIAL SUSTAINABILITY OF AGRO-FOOD SYSTEMS THROUGH LIFE CYCLE APPROACHES

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1 Introduction

Since long time now, academicians, technicians, and practitioners from different disciplines and sectors are constantly discussing (each one from their point of views) on sustainability concerns linked to the management of agricultural and food systems, trying to reflect all different aspects and implications. Although the term “sustainability” can be considered a too easily used word, thanks to its apparent intuitive comprehensibility, it still remains today a concept difficult to put into practice.

Above all, the main difficulty can be attributed to the need of integration of the different sustainability dimensions, environmental, economic, and social. Although the academia is constantly engaged in researches to solve this issue, a formally and worldwide recognized ensemble of frameworks, approaches, methodologies, methods, techniques, and tools, for measuring sustainability, is not yet identified univocally (Ramachandran Nair and Toth, 2016). Furthermore, if the final objective is to comply with sustainability, behavioral changes of entrepreneurs,

brokers, consumers, public agencies, and communities would be more than necessary. In addition, it is crucial to make informed choices and behavioral changes, while tools to measure and communicate sustainability performances become highly suitable (De Luca et al., 2015b). It is necessary a most comprehensive knowledge about whom or what (*subject, product, or service*) generates a certain typology of impact (*positive or negative*), that have to be appropriately characterized and quantified, to suggest sustainability-oriented innovations or changes.

The agro-food contexts are characterized by high levels of complexity, because of their biological features and their strong interconnections with different systems (e.g., land, air, and water systems). The measurement of sustainability should take into account interlinks that have consequences on the environment, the economy, and the society through cause-effect relationships. The agro-food system has the peculiarity of being a *syneresis* of different economic activities which involve both natural processes managed by anthropic actions and industrial processes, fully under human control (De Luca et al., 2015a) (Fig. 1).

Nevertheless, the responsibility of agro-food systems in causing negative externalities confirms the increasing requirement to find new methods and tools for the impacts assessment. Indeed, it is notorious that agro-food productions represent the most polluting economic activities, contributing to environmental damages such as global warming, loss of biodiversity, energy and water resources depletion, and wastes production. At once, the appropriate corrective actions for the mitigation of environmental issues, must conciliate the economic needs of entrepreneurs, related to costs reduction, income stabilization, productivity, and competitiveness (Falcone et al., 2016).

In this attempt to face the sustainability concerns in the broadest manner, the life cycle-based approaches can help to extend and complete the analysis of the problem by a systemic approach considering all phases of production processes (Sala et al., 2013).

In its early conception, the life cycle thinking (LCT) pursued the key objective to reduce the environmental loads and the use of resources by identifying possible improvements to goods and services (EU, 2010). The novel idea of LCT is to consider a product or service as a living being, that is, with a “birth” when the production process starts from raw materials, a “life” in the phase of use by consumers, and a “death” if eventually are discarded (De Luca et al., 2015a). According to UNEP (2005), within this cycle, “from cradle to grave,” the product relates, dynamically, to

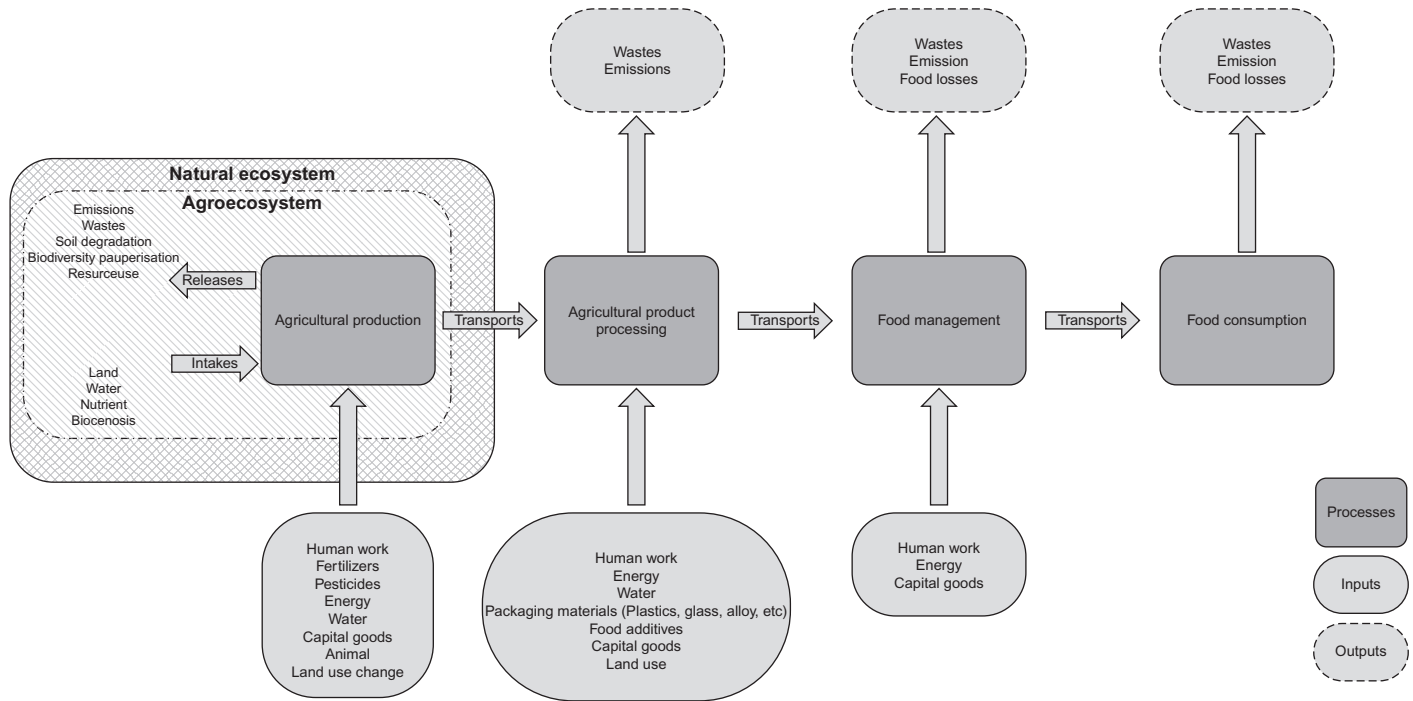


Fig. 1 Example of life cycle framework for agro-food systems.

environmental, economic, and social domains, and this is the reason why, over time, a set of specific tools have been elaborated, within LCT, to evaluate different impacts deriving from the life cycles of goods and services. In particular, as it will be better explained in the following paragraphs, life cycle assessment (LCA) is applied to evaluate the impact of goods and services on different environmental categories. Life cycle costing (LCC) can be used to measure the economic impact of goods and services by analyzing all relevant costs items (both at firm's level and as externalities at societal level). Social life cycle assessment (SLCA) attempts, through different approaches to identify and assess social repercussions and implications generated from goods and services production. An established and shared knowledge about life cycle sustainability assessment (LCSA) (Klöpper, 2008) represents, for the near future, the cutting edge of life cycle-based sustainability approaches. This chapter provides a description of the above-mentioned life cycle methodologies, by stressing their specific backgrounds and approaches and providing a brief overview of the state-of-the-art of the main application in agro-food sector.

2 LCA to Measure Environmental Loads

More broadly, since the 1970s, the environmental protection has gained an increasing attention by politicians, researchers, and communities. Until then, natural resources were only considered as production factors, and their availability was not a concern (De Luca et al., 2015a). In 1973, due to the Kippur war, the OPEC countries (Organization of the Petroleum Exporting Countries) stopped the crude oil flows (Rybczynski and Ray, 1976), showing to the world the limits of growth found on the fossil energies. This crisis, and the awareness about the importance of environmental protection, caught the attention of public opinion and imposed companies to study solutions to limit their pollution and to preserve the natural resources (Hunt and Franklin, 1996).

This context boosted the scientific community to define a new tool, useful for the evaluation of environmental profile of products, processes, and systems, to identify the hotspots and to define corrective solutions (Curran, 1996). Borrowing the framework proposed by Novick (1959) for the economic evaluation of military weapon investments, a new approach was defined for the assessment of environmental burdens linked to the production processes, based on the expansion of the analysis boundaries

(Huppés and Curran, 2012). In 1969, the Midwest Research Institute, working on a commission of the Coca Cola Company to define the better packaging between disposable plastic bottle and reusable glass one, had applied a “cradle-to-grave” analysis by including all materials, energy consumption flows, and emissions for packaging production (Curran, 1996). The same approach, named REPA (resource and environmental profile analysis), was applied by the Mobil Chemical Company, for the agro-food packaging (Sala and Castellani, 2011).

When Boustead and Hancock published in 1979 the “Handbook of Industrial Energy Analysis,” the life cycle approach, based on the REPA method, acquired the reputation of scientific methodology. REPA was used as a starting point for the definition of a new methodology applicable to all products, processes, and systems that provide clear and reproducible results: the LCA. The first definition was coined in the 1990, at the workshop of the Society of Environmental Toxicology and Chemistry (SETAC), when the LCA was presented as “an objective process to evaluate the environmental burdens associated to a product, a process, or an activity by identifying energy and materials usage and environmental releases, and to evaluate opportunities to achieve environmental improvements” (Fava et al., 1991:17).

In 1996, the International Organization for Standardization published the standard 14040 that defined the principles and the framework of LCA methodology (Merkel, 1997). The standard still represents the shared basis for the LCA applications (ISO, 2006a,b) and for a wide range of derived methodologies as the Carbon Footprint (BSI, 2011; ISO, 2006c, 2013), the Water Footprint (ISO, 2014), the Ecological Footprint (GFN, 2009), the Environmental Footprint of Products (PEF), and Organization Environmental Footprint (OEF) (EC, 2013).

The ISO 14040:2006 structures the LCA analysis in four consecutive steps linked each another through an iterative approach that allows the revision of previous steps, if necessary (ISO, 2006a,b).

The first step consists in the definition of the goal and scope of the study, with the definition of the product system and its functions. Furthermore, some parameters characterizing the study have been defined, as the Functional Unit (FU), that is, the measurement unit to which all inputs and outputs data are related—and the system boundaries. These last parameters represent the physical framework of the study object in which all input and output should be included as elementary flow. The definition of system boundaries should be consistent with goal and scope of the study. Furthermore, data description and data quality requirements represent a crucial issue of LCA studies (De Smet and

Stalmans, 1996). In terms of allocation procedures, although the ISO norm (ISO, 2006a) suggest avoiding it and prefers the system expansion, the more widespread choice is the “mass unit” or the “economic value” as criteria for the flows attribution, which inevitably can represent a limitation of the study. Alternatively, specific procedures can be selected to better reflect the product system (Schrijvers et al., 2016). In addition, impact categories have been defined, as well as the methodologies of impact assessment and interpretation. Finally, the assumptions and the limitations of the study should be declared. Substantially, to guarantee the reliability of a LCA analysis, a full clearness of methodological choices and procedures is essential.

The second step is the so-called life cycle inventory (LCI), that is, the collection of data linked to the product system and the following calculation procedures. Data collection consists in the quantification of all elementary flows (input and output) related to all processes included in the system boundaries. They can be briefly described as energy input, materials flows, and emissions to air, water, and soil, use of natural resources, product, coproduct, wastes, and other secondary input and/or output. Since data collection can represent an economic and time expensive step, in the goal and scope definition, only data strictly necessary to the analysis should be considered. Data can be referred to background and foreground processes to understand better the results of analysis; furthermore, data can be derived from primary sources (directly collected), secondary sources (data from third parts), and tertiary ones (data estimated). The accounting procedures consider the statistical assessment of data quality, the operation of scaling to relate the data to unit process and to FU, and the attribution of elementary flows to products in accordance with the allocation choice defined previously.

The life cycle inventory assessment (LCIA) is the third step and entails the evaluation of potential environmental impacts. It is composed of different elements, some of which are mandatory and others optional. The first mandatory element is the selection of impact categories, category indicators, and characterization models. The second element is the classification, in which the LCI results are assigned to the impact categories. Following, the third mandatory element is the characterization, which consists in the calculation of the indicator results from where you get the eco-profile. Other optional elements are represented by the normalization of the impacts, the grouping into areas of protection, and the weighting for the quantification of magnitude of characterization outputs. The LCIA represents a fundamental step because it provides the core results of analysis that can differ

according to the impact assessment method chosen. For this reason, the LCIA must be always consistent with goal and scope (De Luca et al., 2015a).

The final step consists in the interpretation of results, highlighting possible hot spots and burden shifts. Results can be used both by private and public actors to address corrective strategies for improving the production process.

LCA methodology acquired growing consensus in the scientific community (e.g., Parker, 2012; Ghattas et al., 2013; Lovarelli et al., 2016; Notarnicola et al., 2017) and its information are trusted by more conscious stakeholders (Alem et al., 2015; Pullman and Wikoff, 2017). The agro-food sector plays a key role in the development and application of the methodology, being one of the most preferred fields of application by scholars (Notarnicola et al., 2015).

Owing to the different issues related to the sector, and the relevance of food for the society, the agro-food system attracts the attention of scientist and then the LCA literature related to this area of study continues to grow. The most common objective of agro-food studies is the comparison between different scenarios to define the most sustainable product or process (e.g., conventional vs organic), but also supply chains assessment represents an important goal to pursue (De Luca et al., 2014; Gresta et al., 2014; Falcone et al., 2015). Many scientific papers can be found regarding the different supply chains of agro-food sector, but the most debated one is about the livestock productions (Roma et al., 2015; McAuliffe et al., 2016; Baldini et al., 2017), due to their impacts on the environment.

Agriculture is responsible for about the 10% of total GHG (greenhouse gas) emissions, while over the 65% of global agricultural emissions of CO₂ equivalent are produced by livestock and connected activities, because of the large amount of CH₄ released during enteric fermentation (the 40% of global emission) and NO released during manure management (FAOSTAT, 2017). Also in terms of resources depletion, the livestock production can be considered one of the largest contributors.

Considering the water footprint of total agricultural production of 8363 Gm³ year⁻¹ the animal production accounts about 29% (Mekonnen and Hoekstra, 2012). The relevance that this supply chain assumed in terms of LCA studies boosted the development of specific LCA-based tools, such as FAO Livestock Environmental Assessment and Performance (LEAP) Partnership (LEAP, 2014). This is a significant issue considering the growing awareness of consumers for environmental impacts due to livestock farming, which is one of the reasons of changing diet of

people. This recent trend is leading to deepen increasingly the research on eating habits to understand their potential impacts in terms of environmental sustainability (Sturtewagen et al., 2016; Hallström et al., 2015; Pairotti et al., 2015).

Another field deeply investigated by LCA researcher concerns the perennial crops (Falcone et al., 2016) and the issues related to their agricultural and industrial phases. Apple and citrus are the most studied fruit production (Cerutti et al., 2015). The processed agricultural products characterized by two-production phases, agricultural phase and industrial, are widely analyzed due to the complexity of their systems in terms of modeling choices. Among all, the olive oil production is the most deepened sector (Cappelletti et al., 2014; Russo et al., 2016; Pattara et al., 2016), representing one of most important agricultural production of Mediterranean area.

Also, wine and fruit juice productions are object of analysis by reason of common issues (Beccali et al., 2010; Dwivedi et al., 2012; Chiusano et al., 2015; Falcone et al., 2016), in the “farming phase” and in the modeling of the biotic phenomena and their interaction with anthropic activities (Cerutti et al., 2015).

In particular, the dispersion of fertilizers and pesticides represents one of the most important unresolved issues for LCA practitioners, who have to manage with calculation models or generic assumptions to estimate the fate of these factors (Bouwman, 1995; Brentrup et al., 2000; Margni et al., 2002; Birkved and Hauschild, 2006; IPCC, 2007). Indeed, due to the complexity of interactions existing in the ecosystems, the study of effects of the dispersion of these substances on the environment need more efforts. In this matter, one of the most interesting field of study is about the methodological advances of LCA implementation in terms of land-use analysis (Koellner et al., 2013) and water depletion (Pfister et al., 2009), especially after the publication of ISO norm 14046 on water footprint of products (ISO, 2014).

The research on agro-food sector is highly dynamic as proved by the increasing number of contributes presented during the last two International Conferences on LCA of Food (Schenck and Huizenga, 2014; LCA Food Conference Committee, 2016). However, the farm production still represents the phase in which several issues need greater research efforts. In particular, LCA experts’ community needs to solve some problems related to the responses of biological systems to farming operations, to the impacts of land transformation and occupation, and to the water use and consumption. These environmental questions afflict the agro-food sector (EEA, 2012) and represent the most important challenges for the future (Notarnicola et al., 2012).

3 LCC to Evaluate the Profitability of Agro-Food Companies

Although as early as 1933, in the United States, life cycle costs were already included in operating and maintenance costs following the purchase of tractors from the General Accounting Office, LCC was not yet born as a methodology. The first attempt was made in the 1960s when the US Department of Defense evaluated investment costs of military equipment. From 1970, also in the United States, many regulations have been issued that required the evaluation of life cycle costs for decisions involving the acquisition of public buildings. In Europe, LCC technique has spread in the public sector since the mid-1970s. Therefore, this approach, named conventional LCC, has mainly been used as a decision support method for investments. Compared to others traditional cost-accounting techniques, LCC considered all costs related to the entire life cycle of a product or system, from development to its disposal, allowing an optimal budget allocation and a better business performance (Gluch and Baumann, 2004; Huppel et al., 2004; Lichtenvort et al., 2008; Hoogmartens et al., 2014).

Since the 1980s, several standards (AS/NZS, 1999; ISO, 2000–2001; ISO, 2008) and different methods (Dhillon, 1989; Ellram, 1993, 1994) concerning harmonizing and performing Conventional LCC have been developed. As argued by Emblemvåg (2003), most of the LCC approaches are cash flows models in which all future costs are discounted to their present value. In this sense, the economic evaluation is usually done from a solely financial point of view (Ciroth et al., 2016). However, Lichtenvort et al. (2008) debated that a generally applicable methodology has not explicitly evolved.

As observed by Gluch and Baumann (2004), due to the increasing interest on environmental issues, several LCC-oriented corporate environmental accounting tools have been elaborated and used in an investment decision process. Nevertheless, the same authors argued the need to improve and implement these methodologies for environmental decision-making. In 2002, with the aim to identify current practices concerning LCC, the SETAC-Europe Working Group distinguished the following three types of LCC (Ciroth et al., 2008). The first is named Conventional LCC, a quasidynamic model that evaluates only real, internal costs associated with the life cycle of a product. The second, Environmental LCC, which assesses internal costs including externalities, that are anticipated to be internalized in the decision relevant future; this type of LCC also involves a complementary

LCA analysis, with equivalent system boundaries and FUs. The third is the so-called Societal LCC, which assess internal and external costs in public organizations and in combination with LCA.

In the same year, the integration of LCC and LCA needed to ensure an assessment of the economic and environmental implications in a consistent sustainability framework was debated during the kick-off meeting of the SETAC (Rebitzer and Seuring, 2003; Lichtenvort et al., 2008). As argued by Norris (2001), both tools have major methodological differences concerning purpose, accounting principles, system boundaries, and treatment of time. Specifically, LCC considers all activities causing cost and benefit monetary flows during the life cycle of a product from a single-stakeholder perspective, whereas LCA takes into account all processes related to the physical life cycle of the product including background processes (Ciroth and Franze, 2009) from a multistakeholder perspective. Since then, several attempts have been made to overcome the difference existing in the computational structures of the two methods (Rebitzer and Hunkeler, 2003; Schmidt, 2003; Hunkeler et al., 2008; Settanni, 2008).

Within the international scientific debate on sustainability assessment, Environmental LCC (ELCC) has attracted a lot of interest. It has been defined by Klöpffer (2003:157) as the “logical counterpart of LCA for the economic assessment,” which overtakes the mere cost accounting by considering “the use- and end-of-life phases and hidden costs” (Klöpffer, 2008:89). Klöpffer and Ciroth (2011) argued that ELCC is entirely compatible with LCA and allows evaluating the costs of product from different actors. In 2011, SETAC published a code of practice for ELCC, which is founded in a conceptual framework for LCSA of products (Swarr et al., 2011a; Klöpffer and Ciroth, 2011). The code of practice provides a solid understanding for applying “LCC in parallel with LCA to stimulate additional case studies and peer-reviewed research to refine further the methodology. Its objective is to build consensus for an international standard that parallels the ISO 14040 standard for LCA” (Swarr et al., 2011b). Nevertheless, as observed by Heijungs et al. (2013) this code does not identify any formula to use. The same authors have developed a matrix-based approach that can be applied to both physical and monetary flows for adapting the computational structures of ELCC and LCA. However, a study conducted by Moreau and Weidema (2015) has challenged the validity of this research, emphasizing some conceptual errors in the methodological approach.

Focusing on LCA-LCC combined applications to food products, Roy et al. (2009) revealed that LCC can be used as a decision support tool within LCA of food products. From a microeconomic perspective, as showed by Settanni et al. (2010a), the scientific literature provides few applications of LCC to food products. Moreover, from a practical point of view, two alternative approaches are mainly used for: (a) applying Conventional LCC as a discounted cash flow analysis, which is performed separately from LCA; (b) integrating LCC with LCA through the adoption of a common database, considering the same FU and system boundary, and assessing in monetary terms the physical flows resulting from the LCI. In Fig. 2, an inventory costs complementary to LCA inventory is represented as established in ISO (2006a). Nevertheless, consistency issues when one tries to integrate LCA and LCC need to be taken into account. To overcome this difficulty Settanni et al. (2010c) proposed an input-output analysis (IOA)-based approaches, which allow carrying out LCC in the same holistic way as LCA. From a supply chain management perspective, the application of such approaches allows to assess the economic performance of a supply chain including environmental concerns, even though further academic research is needed (Notarnicola et al., 2015).

However, over the last years, ever-growing attention has been devoted to the development of applications in the agro-food

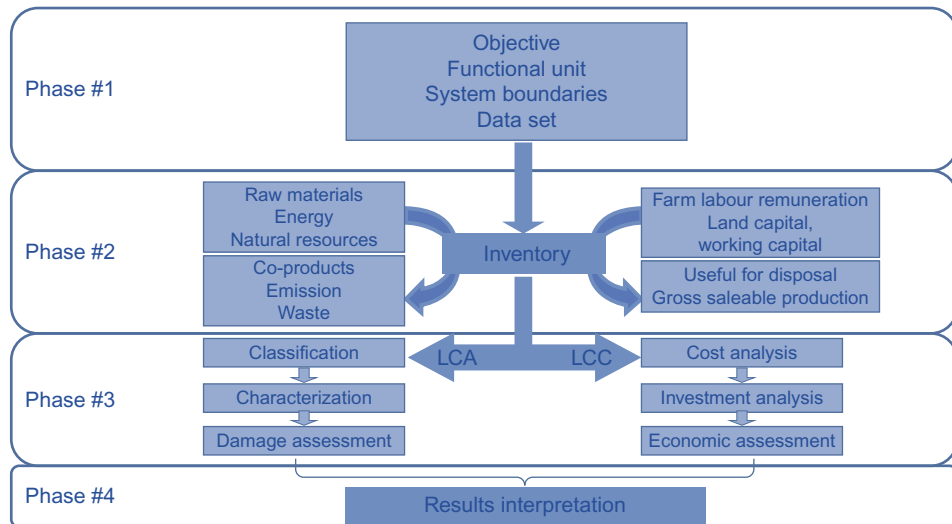


Fig. 2 Suggested framework for integrating environmental and economic inventory data.

sector. In a recent critical review performed by [Notarnicola et al. \(2015\)](#), with the purpose of highlighting current practice regarding LCA for the agro-food sector, applications of LCC to food products have been identified.

Focusing on olive oil sector, [Notarnicola et al. \(2004\)](#) assessed the environmental and cost profiles of the conventional and organic extra-virgin olive oil production by using LCA and LCC methods, to identify both the eco-compatibility of organic extra virgin olive oil compared to the conventional one and the reasons for higher market price of the organic oil. In a comparative study, [De Gennaro et al. \(2012\)](#) investigated on the integrated application of LCA and LCC, by using a model of LCC based on IOA to evaluate the environmental and economic performances of two innovative olive-growing systems. [Mohamad et al. \(2014\)](#) had integrated LCC with LCA to study the economic dimension and environmental impacts of two organic and conventional olive production systems, aiming to recognize the hotspots of each system for both the optimization of olive agricultural practices and the potential reduction of environmental loads. Recently, [Christoforou et al. \(2016\)](#) conducted a feasibility analysis of the entire supply chain of the olive mills solid waste pellets by means of LCC model, which considers the energy costs, the operational and maintenance costs, transportation costs, and the final costs. [Stillitano et al. \(2016\)](#) compared different olive production systems through a joint use of LCC method and economic indicators (net present value, internal rate of return, and ratio between benefits and costs) to estimate their economic profitability. In a study conducted by [Taousanidis and Gavros \(2016\)](#), the economic viability of a photovoltaic pumping system for olive orchards as an alternative to the classic diesel pump irrigation was carried out. The authors have used the LCC analysis to compare the two irrigation alternatives, taking into account all parameters affecting on these systems such as capital cost of the components, installation, structures, fuels, operating, and maintenance costs.

Concerning citrus fruit sector, [De Luca et al. \(2014\)](#) examined the level of sustainability of Clementine crop systems from both an economic and environmental perspective, through a joint use of LCA and LCC. [Pergola et al. \(2013\)](#) carried out an energy, economic, and environmental analysis by using EA, LCA, and LCC analyses to compare organic and conventional farming systems of lemon and orange productions.

In wine growing sector, only few studies assessed the economic performance of grapevine production systems by means

LCC and LCA. This is the case of [Strano et al. \(2013\)](#) and [Falcone et al. \(2015\)](#), who analyzed and compared different vineyard production scenarios from both an economic and environmental standpoint through a combined LCA-LCC methodology. To make a sustainability assessment of different wine-growing scenarios that combines conflicting insights (environmental and economic ones), [Falcone et al. \(2016\)](#) have applied LCA and LCC approaches to identify main hotspots and selecting the alternative scenarios closest to the ideal solution through the VIKOR multicriteria method.

[Amienyo \(2012\)](#) performed a comparative analysis in the beverage sector by coupling LCA, LCC, and social indicators to assess the environmental, economic, and social sustainability of different beverage subsectors and identified the hotspots that could be targeted for improvements. Recently, [Amienyo and Azapagic \(2016\)](#) applied the LCC methodology in a congruent manner with the LCA approach to estimate the life cycle environmental impacts and costs of beer production and consumption.

Regarding cereal and derived products sector, [Settanni et al. \(2010b\)](#) applied a model of LCC based on IOA to fresh pasta production. In this paper, the authors proved the effectiveness of this novel-costing model as it is consistent with LCA, sharing a similar computational structure. Relatively to livestock and derived edible products sector, the combination of LCA with the evaluation of economic impacts by using LCC, net present value, and value added, has been carried out by some studies. This is the case of [Weidema et al. \(2009\)](#) and [Basarab et al. \(2010\)](#), who examined the environmental and economic performance of meat and dairy products, and beef production, respectively. To evaluate the environmental and economic impacts LCA and value added were developed. [Van Middelaar et al. \(2011\)](#) investigated the level of sustainability of the cheese production chain, by quantifying the ecological impact using LCA and by determining eco-efficiency of each stage along the chain as the ratio of gross value added to ecological impact. [Oishi et al. \(2013\)](#) analyzed economic and environmental impacts of changes in culling parity of cows and diet composition in beef cow-calf production systems using LCA and annualized net revenue, respectively. For the industrial phase of Parma PDO ham production, [Iotti and Bonazzi \(2014\)](#) performed an exclusive LCC analysis to quantify the cost of production in the long-term operation in the processing of pig meat. Finally, with the purpose to identify production systems of beef cattle that allow reducing the greenhouse gas emissions and, concomitantly, are economically viable. [Florindo et al. \(2017\)](#) used LCC in conjunction with

investment analysis tools (net present value, internal rate of return, and annualized profitability index) and LCA.

Brandão et al. (2010) considered a combination of conventional cradle-to-gate LCC and LCA to set out an integrated economic and environmental sustainability assessment for comparison of different land-use systems (wheat and oilseed rape, Scots Pine, and willow and *Miscanthus*) for food, timber, and energy production. Schmidt Rivera and Azapagic (2016) have also integrated LCC with LCA to estimate the economic aspects and environmental impacts of ready-made meals, in comparison with the equivalent meals prepared at home.

Some other studies relate the economic costs and the environmental impacts of rapeseed cultivation systems by means of LCC combined with LCA. This is the case of Baquero et al. (2011), who carried out an LCC-based economic feasibility evaluation, by following the LCA approach, of a self-supply farming model that introduced rapeseed to the traditional crop rotation (wheat and barley), to use it as fuel base and replacing diesel fuel. Even though the study conducted by Palmieri et al. (2014) focused on environmental impacts assessment of rapeseed production, an evaluation of the economic costs, following the LCA-type LCC method, was approached to estimate the feasibility of an integrated assessment of firm's performances.

A growing amount of literature in agro-food sector is aimed at integrating social issues in LCA and LCC studies within the context of LCSA. For example, Albrecht et al. (2013) used joint application of LCC, LCA, and life cycle working environment methodologies to examine and compare the most common transport packaging systems in the fruit and vegetables sector, with respect to the environmental impacts and social and economic aspects related to their use. The LCC analysis was performed within the same system boundaries as the environmental baseline scenario. De Luca et al. (2015c) proposed a new approach that combines participatory and multicriterial tools in an SLCA application by integrating, simultaneously, environmental, and economic indicators collected from LCA and LCC analyses. This study focused on different citrus-growing scenarios to rank the social performance of each case and to reflect on the most critical steps in conducting an SLCA. Tamburini et al. (2015) had firstly identified the most critical environmental and economic hotspots of different agricultural productions (organic tomato and pear, integrated wheat, apple, and chicory) through LCA in conjunction with LCC and, secondly, had estimated the externalities to quantify the socio-economic long-term impacts of the agricultural products combining the results from LCA and LCC analysis.

4 The Evaluation of Social Impacts in a Life Cycle Perspective: SLCA

SLCA is the latest tool developed within the conceptual framework of LCT. Even if the necessity of integrating social aspects has been felt as important since the 1990s (O'Brien et al., 1996), academicians struggled to find consensus on a univocal procedure for SLCA. Indeed, the state-of-the-art methodology is a variegated scenario composed of many different proposals and perspectives (Iofrida et al., 2016). All these proposals differ in many ways, such as in term of:

- what is considered being the source of impacts, for example, the companies' responsibilities (like corporate social responsibility—CSR in management and accounting research), the very nature of the product or service, or both;
- which is the underlying social sustainability concept, often more or less explicitly referred to the “three pillar model” or “triple bottom line” (Elkington, 1998);
- which steps to follow, that is, the same steps of LCA according to ISO (2006a,b);
- which assessment scale to be applied, that is, local or global, company or sector level;
- what is the concept of impact and, therefore, the object of assessment, for example, performances (considered as the results of actions implemented in a given moment) or consequences (considered as effects quantitatively related to their causes).

Developed to be the social peer of LCA, forcing the realm of social phenomena into the engineering rules of the environmental assessment practices has not been without difficulties. In fact, taking into account the typical standardized steps of LCA (ISO, 2006a,b), some considerations are necessary when moving to social phenomena assessment:

- Goal and scope phase. As in LCA, choices in this phase are mainly at discretion of researchers. G and S provides information about the objective of the assessment, the background, the rules applied, as well as the system boundaries, the cut-off criteria, and the FU (Klöpffer, 2014), that is, those elements necessary to describe what is considered in the study (foreground and background), what is excluded from the system, and to which unit of product or process impacts are referred. In SLCA boundaries are not physical, or at least not only, but concern relationships among actors and/or among technical systems and actors (Parent et al., 2010;

Lagarde and Macombe, 2013); their choice can strongly affect results (Zamani et al., 2015); however, in SLCA studies justifications for system boundaries setting is often lacking or not systematized (Dubois-Iorgulescu et al., 2016). Concerning the FU, since the beginning CSR strongly influenced SLCA applications, which undertook therefore a company perspective: the possibility of relating companies' behaviors and territorial specificities to a physical FU has been called into question (Zamagni et al., 2011). In fact, few studies used a FU in SLCA (Petti et al., 2016), such as for example: tons of exported bananas in Feschet et al. (2013), one airbag system in Baumann et al. (2013), 1 m of weld seam in Chang et al. (2015), 1 ha in De Luca et al. (2015c).

- LCI. This phase concerns the gathering of data to be then elaborated. The inventory in environmental LCA mainly concerns physical flows of materials and energy. Depending on the approach undertaken in SLCA, data could be of different nature, therefore physical (quantities of inputs and outputs) but also immaterial, such as opinions or behaviors. This phase is strongly influenced by the objective of analysis and the impact assessment method applied, that in turn depends by the theoretical underpinnings of the study (Iofrida, 2016; Iofrida et al., 2016). It is not unusual, in SLCA, to collect or validate inventory data by means of interviews and questionnaires involving relevant stakeholders (Manik et al., 2013; Hosseiniou et al., 2014; De Luca et al., 2015c; Siebert et al., 2016). Other recurrent techniques for data collection are represented by literature reviews, statistical databases, and gray literature. In the last years, the social hotspot data base has been set up by Benoit et al. (2010), based on the indicators list suggested by UNEP-SETAC (2009, 2013); it allows to make sectorial assessments for many products and countries from statistical data.
- Life cycle impact assessment. This phase represents the core concerning SLCA, and the main point of discordance among the methodological proposals published until now.

Firstly, impact assessment methods differ in terms of object of analysis such as the social performances (e.g., UNEP/SETAC, 2009; Bouzid and Padilla, 2014; Petti et al., 2016), the occurrence of hot spots (Benoît-Norris et al., 2012; Ekener-Petersen and Moberg, 2013), the consequences on people and societies (Feschet et al., 2013; Bocoum et al., 2015), opportunities (Siebert et al., 2016), and the involvement of stakeholders (Manik et al., 2013; Mathé, 2014), also by means of

multicriteria decision analysis (Halog and Manik, 2011; De Luca et al., 2015c).

Secondly, the impact assessment methods themselves can be very different. Since the beginning, academicians and practitioners claimed the need for including social impacts in LC tools, following the same procedures applied for environmental ones. However, the methodological proposals published until now took different directions. The main reason of this diversity has been explained by Iofrida et al. (2016): LCA and SLCA have their roots in different families of disciplines, such as natural sciences (mathematics, biology, chemistry, physics, etc.), and social sciences, respectively. While in natural sciences postpositivist paradigms are commonly applied and well accepted, social sciences are multiparadigmatic and many epistemological positions can be held; as a consequence, social impacts can be assessed and studied in many different ways, according to the worldviews of the researcher.

In fact, examining the scientific literature, two main groups of assessment methods can be found. A first one, that we call “interpretivist,” is inspired to type 1 impact assessment by UNEP/SETAC (2009, 2013), that is the so-called guidelines, and is mainly oriented to companies’ behavior and social performances, as well as social values, international rights, and stakeholders’ desiderata. In fact, data are mainly gathered by means of qualitative techniques such as interviews, surveys, questionnaires, focus groups, and so on. Most indicators have been proposed focusing on the typologies of actors potentially involved in a life cycle. Most of the studies belonging to this group apply “static indicators” that allow to describe a current situation at a certain moment. No information is provided about the consequences if the system assessed would change, or about the causes of the positive or negative performances in the long period. On the other hand, using a wide number of indicators allows us to catch many characteristics of the system and impact categories (like a “snapshot”), to take into consideration what is worthwhile for actors, such as their values and concerns. The aggregation of subcategories into stakeholder dimensions is mainly conducted by means of value judgements through scoring and weighting but, according to Do Carmo et al. (2017), this brings higher levels of uncertainties related to these value choices. Also the social hotspot database is applied by scholars belonging to this group.

A second group of methods, called by Iofrida et al. (2016) “postpositivist,” is mainly oriented at assessing the cause-effect relationships, quantitatively measurable, between the physical

system under study and consequences on people and society. Data are mainly (but not only) gathered by means of statistical databases (such as input-output tables). This approach is epistemologically in line with LCA. To this group belongs the so-called impact pathways, firstly introduced by [Weidema \(2006\)](#), [Norris \(2006\)](#), and then explored and applied by [Macombe et al. \(2013\)](#), [Feschet et al. \(2013\)](#), [Silveri et al. \(2014\)](#), [Neugebauer et al. \(2014\)](#), and [Bocoum et al. \(2015\)](#). The strength of this kind of methodology is that it allows formulating expectancies, but, on the other hand, few pathways have been developed, they can be applied at certain conditions, so currently they enable to study just few impact categories.

Interpretation. The interpretation phase has the same objective as in the other LC tools, that is, communicating results to the addressees of the study, providing information for decision-making processes, and so on. The typology of information provided (a description or an explanation) depends on the methods applied. This phase is one of the most subjective ones in all LC tools; when more social impact categories are assessed, or more LC tools are applied to the same case study, combining results, especially conflicting ones, can be difficult. To overcome this kind of issues, many authors apply multicriterial methods to assign different weights according to possible different stakeholders' opinions, such as local actors, workers, or experts ([De Luca et al., 2017](#)).

Concerning the application of SLCA in literature, agricultural and food products have been among the most assessed; the impacts of agriculture on people and communities are in fact widely recognized ([De Luca et al., 2015a](#)). Agricultural products for fresh consumption, processed products, fishery, and dairy products have been under the attention of scholars; more details are discussed in [Table 1](#).

As shown in [Table 1](#), the impact assessment methodology varies from one author to another. The guidelines by [UNEP-SETAC \(2009\)](#) have had some consensus, but a unique methodology is still far to reach. The typology of indicators applied is variegated and referred to different stakeholders, such as workers (the most assessed category of affected actors), consumers, and citizens. The common point of many studies is about the participation of stakeholders (workers, farmers, local actors, experts), involved in selecting the indicators or in weighting the assessment criteria.

Table 1 SLCA Applied to Agro-Food Products

Reference	Product Assessed	Impact Assessment Method, as Declared by Authors	Main Results or Conclusions, as Declared by Authors
Andrews et al. (2009)	Greenhouse tomatoes	Attribute LCA, labor hour satellite matrix	At least 75% of the product system had the attribute of interest on five of eight indicator categories
Kruse et al. (2009)	Salmon production system	Additive and descriptive assessment	Indicators are categorized based on fundamental methodological differences and then used to describe the socioeconomic impacts associated with salmon production
Benoit-Norris et al. (2012)	Strawberry yogurt	Social hotspot database (SHSD)	Site-specific data are required to inform decision-making and to help improve the social performance of at-risk node of the supply chain
Feschet et al. (2013)	Bananas	Preston pathway	The future activity of company would improve the potential life expectancy of Cameroon population by 5 days over 20 years, exporting 200,000 t of bananas annually (in comparison with no activity)
Bouزيد and Padilla (2014)	Tomatoes	UNEP-SETAC guidelines	The most profitable segments of the production chain are those that present better working conditions, but the agricultural production shows the greater social difficulties
Mathé (2014)	Fisheries	Participatory approach	Participation enables to be taken into account stakeholder interests, local knowledge, and impact categories that make sense for stakeholders in different contexts
Ramirez et al. (2014)	Wine sector	UNEP-SETAC guidelines, subcategory assessment method (SAM)	Not all specific situations can be taken into account with Sam methodology
Smith and Barling (2014)	Food and drink sector	Top-down and bottom-up approach	The complexity of the SLCA approach stays in combining disparate and often conflicting interests
Bocoum et al. (2015)	Maize and grape vines	Wilkinson pathway	This pathway put in relation the probable effects of a change in the life cycle with income inequality and then infant mortality
De Luca et al. (2015a,b,c)	Clementine	Participatory approach	Scenarios have been evaluated according to stakeholders' preferences that made the assessment locally relevant and legitimate
Nemarumane and Mbohwa (2015)	Sugar cane	UNEP-SETAC guidelines	Workers are the most affected actors

Continued

Table 1 SLCA Applied to Agro-Food Products—Cont'd

Reference	Product Assessed	Impact Assessment Method, as Declared by Authors	Main Results or Conclusions, as Declared by Authors
Revéret et al. (2015)	Milk	UNEP-SETAC guidelines, social hotspot database	The model can serve as a basis for a self-assessment tool for farmers, to improve their management and to identify best practices
Vavra et al. (2015)	Food industry	UNEP-SETAC guidelines and qualitative weighting	The assessment of social impacts represents the difficult but necessary improvement of social interactions between companies and stakeholders
Arcese et al. (2016)	Wine sector	UNEP-SETAC guidelines	The application of SLCA in a sector as the agro-food, characterized by a strong link with the territory, requires the creation of indicators to assess the effects of the unavoidable synergy
Petti et al. (2016)	Tomato	UNEP-SETAC guidelines and SAM	More organizations along the life cycle must be taken into account
Chen and Holden (2016)	Dairy farming	UNEP-SETAC guidelines	Possible actions to improve the social performance include introducing more efficient and robotic milk production systems

5 Conclusions

Agro-food sustainability assessment has to be addressed, necessarily, with the right mindfulness in considering the multifarious aspects and implications that characterize this complex domain. The distinctive features of agro-food production requires a significant knowledge effort aimed to define new methodologies, by moving towards a holistic evaluation of problems. Life cycle approaches can represent a suitable set of tools to recognize, characterize, analyze, determine, quantify, and understand impacts, repercussions and effects of a different nature generated by a production process. Although with their specificity and complexity of application, LCA, LCC, and SLCA offer a powerful means to compare production techniques (traditional vs innovative) and typologies of food products, and to provide useful guidelines and practical suggestions to apprise and advise private and public subjects on sustainable pathways. This chapter aimed to provide an overview of life cycle tools by highlighting their significant and principal characteristics and reporting different applications in agro-food contexts.

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SYSTEMS FOR SUSTAINABILITY AND TRANSPARENCY OF FOOD SUPPLY CHAINS

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1 Introduction

Székely and Knirsch (2005) proposed that sustainability is the building of a society in which a proper balance is created between economic, social, and ecological aims. That is, reflecting on the triple bottom line (TBL). Sustainability has multiple definitions, aspects, methodologies, and interpretations (Aiking & de Boer, 2004), and has been said as a concept to encapsulate risk mitigation and business improvement and has the potential for reducing the long-term risks associated with product liabilities, resource depletion, fluctuations in energy costs, pollution, and waste management (Shrivastava, 1995). From product design to postconsumer product management, sustainability is an important issue, but its consideration in supply chain management (SCM) is argued as lagging behind (Fritz et al., 2017). Sustainability has been described as the capacity of a system, within a given degree of variability, to maintain output at a level approximately equal to or greater than its historical average (Lynam & Herdt, 1989), that is, sustainability reflects a management function to produce the same or more output than in the past from the same or less resources. Enhancing the sustainability of a given product, where/what it is to be sustainable is determined by stakeholders and ultimately consumers can lead to added value being derived from the processes employed at different steps in the food supply chain. These extrinsic process characteristics can, for example, be higher welfare attributes, defined methods of production such as free-range or organic systems and as such the inherent additional

value in the resultant food product can translate to higher prices. [Lynam and Herdt \(1989\)](#) determined that the overall supply chain sustainability is not dependent on every subsystem within the food supply chain being individually sustainable. Instead it reflects the sum of the whole, that is, the capacity of the system rather than all activities individually mitigating or adapting to long-term sustainability risk ([Manning & Soon, 2016a](#)). Thus, sustainability at the food supply chain level could be said to reflect the capacity of the entire supply chain system to be sustainable rather than all the activities or enterprises having independently determined and mitigated long-term sustainability risk. Indeed where some supply chain actors can be readily substituted in a given food supply chain, for example, alternative sourcing at the business, geographic region, or commodity level, the overall supply chain or even product life cycle can be argued to be sustainable even if at one level of the supply chain the mode of operation clearly is not sustainable in terms of one or more TBL characteristics. This theme is further explored in this chapter when considering the aggregation of sustainability metrics whereby weak performance in one element of a metrics-based scoring system can be subsumed within an overall aggregate score.

Organizations, within a supply chain, exist in a context that is intrinsically complex, and increasingly interconnected both socially and technologically ([Annarelli & Nonino, 2016](#)) with multiple processes, value chains, actors, and interactions and the outcomes of supply chain activity affect multiple stakeholders in diverse and sometimes conflicting ways ([Tendall et al., 2015](#)). Indeed, a cascade effect can occur where small shocks at the primary stage of the supply chain can amplify ultimately impacting on individuals at a global scale ([Macfadyen et al., 2015](#)). *External* supply chain stakeholders include shareholders and investors, insurance companies, social and the printed media, and non-governmental organizations (NGOs). Each of these external stakeholders will act owing to a set of motives, goals, or to achieve certain outcomes, for example, shareholders will place emphasis on ensuring any inherent risk to their financial investment is addressed by strategic planning processes ([Manning & Soon, 2016b](#)); insurers will wish for potential supply chain risk to be mitigated to safeguard their need to pay out on an insurance claim; and NGOs seeking to promote standards with regard to often a single issue such as animal welfare or environmental impact. The *internal* stakeholders within the food supply chain include producers, processors, packagers, distributors, transportation companies, wholesalers, supermarket retailers, and consumers

(Macfadyen et al., 2015, p. 4), but they note it is food retailers that hold the pivotal role in the supply chain in terms of vulnerability as well as being the central stakeholder who can drive mitigation activities. All these stakeholders play a role in characterizing what is considered to be sustainability in the supply chain. Springmann et al. (2016) argued that emissions pricing of food commodities, that is, at the primary end of the chain in terms of greenhouse taxes, could have a role to play in climate change mitigation and developing a health-promoting climate policy, that is, that sustainability should be coercively driven through regulation and policy rather than through the market. This chapter explores the status of management systems that support sustainability as a concept in food supply chains and the communication of information to essential stakeholders. The role of transparency and integrity in the management of complex food supply chains is also considered.

2 Sustainability: A Globalism or Globalization Issue?

Keohane and Nye (2000, p. 105) described globalism as:

a state of the world involving networks [or multiple linkages] of interdependence at multi-continental distances ... through flows and influences of capital and goods, information and ideas, and people and forces, as well as environmentally and biologically relevant substances such as acid rain or pathogens.

This interdependence creates reciprocal effects, they argue not only at the nation level, but also at the actor or stakeholder level. Advocates of globalism extol the virtues of the free transit of capitals, goods, services, and people (Arditi, 2004). An increase in this reciprocal effect can be categorized as globalization, the reverse being deglobalization, that is, globalism as a mechanism can increase or decrease (Keohane & Nye, 2000). Globalization describes a set of changing conditions that transcends the notion that the nation state is a fundamental unit in terms of organization, democratic processes, or political units (Thompson, 2012). Further, globalization has led to high-level policy processes such as international meetings between governments and multinational organizations that lack accountability (Lang & Heasman, 2015). Thompson (2012) states that it is difficult to simply classify globalization into a single force or factor such as economic, cultural, political, immigration, new communication or technology, or other factors. Instead globalization can be considered as a

multiplicity of agendas and dialogues indeed as “a many-headed beast [possessing] a plethora of brains and snapping jaws extending from a single body” (Thompson, 2012, p. 60). Szántó (2001) determined that it is “a peculiarity of globalization” that through technological integration and market harmonization, an executive in a multinational corporation (MNC) has a global singular impact, but conversely globalization as a process itself drives inequality and a deepening fragmentation.

Universality is not an innate characteristic of globalism; in fact, it could be postulated that globalization drives inequality in terms of the increasing gap between the rich and the poor and a greater global heterogeneity in access to information and opportunity (Keohane & Nye, 2000). Indeed as some communities become more interconnected and interdependent, Keohane and Nye state that this creates a greater gap for those who are unable to access the technological advances that have driven the benefits of globalism for others. Ardit (2004, p. 6) agrees asserting that globalization has three salient aspects: “the deepening gap between rich and poor countries, the creation of a mobile elite and an increasingly confined mass, and the resurrection of more rigid and less liberal models of identity as a defensive reaction to the dislocations brought upon by globalization under the guise of globalism.” Keohane and Nye (2000) determined four types of globalism and while military globalism is not discussed here, the other three elements reflect considerations on the construct of sustainability and the so-called TBL:

- *Economic globalism*: the interconnected flow of goods, services and capital, information and ideology across multinational boundaries;
- *Environmental globalism*: the movement of materials in given mediums across long distances either through conscious (induced by human activity) or unconscious (natural) means that affect human health and well-being. This could be within the atmosphere such as carbon dioxide, chemical use or air pollution, in the oceans and/or through the transport of plants and livestock with regard to movement of pathogens, wider related plant and animal disease, or the movement of genetic material; and
- *Social and cultural globalism*: the movement of ideas, information, images, and people. The creation of uniformity between societies and, in the context of this book, around the context of food and food supply.

The drivers of globalism may start at the military or economic level, but other elements of environmental, social, and cultural globalism will follow. The question arises whether once this

process develops there is an element of mutual refueling of the elements of globalism from each other, for example, as resources are exhausted in one location in terms of the five capitals (natural, human, physical, social, and financial) whether the globalism model just changes the networks and linkages to exploit capital assets in other global environments. The globalism model has no construct for the societies, communities, and individuals left behind in this process in terms of environmental depletion (loss of soil, water, polluted natural environments, or loss of biodiversity), economic depletion (loss of jobs, opportunities, or access to finance), and social and cultural depletion (loss of societal infrastructure and connectedness). This has fuelled the widening gap between the advantaged and the disadvantaged, a void that is ultimately filled with new constructs around the notions of corporate responsibility and sustainable development and new labels for community groups left behind in such depleted circumstances such as “The Rust Belt” in the United States.

People are agents within economic globalism in terms of being considered as a resource, simply as human capital, often devoid in that respect of social and cultural consideration. Within environmental globalism people can be considered not only as carriers of pathogens and disease (e.g., the 1918 influenza epidemic, H5N1 avian influenza) and through their actions as creators of pollution, but also within social and cultural globalism as the agents of ideas and information. As such, humans lie at the heart of the overall debate on sustainability in terms of how individuals and communities are perceived and the multiple dialogues that surround them. What it is to be sustainable therefore focuses ultimately on how people live their lives, relate to others; and notions of sustainable globalism ultimately have to reflect on the wide gap that the phenomenon has created between those individuals that are advantaged and those that are disadvantaged by the process. Further, as was shown in the banking crisis of 2008, decisions made within one element of globalism, in this case economic globalism, can have far reaching consequences within other aspects such as social, cultural, and environmental globalism. Just as economic gain and benefit can be contagious within this model so too can economic loss especially as economic models continue to evolve in this seemingly uniform and isomorphic model.

Keohane and Nye (2000) proposed consideration of the density of networks within globalism and the influence of network effects and how as interdependence within networks becomes “thicker” systemic relationships become more important, giving rise to the notion of global contagion. Thus as the degree of globalism increases, the potential for uncertainty or risk to arise in one

location and then having influence on another sometimes seemingly disparate community or society also increases. This hypothesis allows for reflection on what it is for food supply chains to have resilience and the mixture of models required within the food supply chains to minimize shock and to ensure that contagion of this nature ultimately does not cause food supply networks to falter or fail. The just-in-time approach to food storage brought in at the end of the last century, means that global food stocks are often minimal. Further, the trend of reducing the number of suppliers and stock inventories in the food supply chain means that risks that cause transportation disruption especially when fractures in global logistics can quickly immobilize supply chains (Giunipero & Eltantawy, 2004), suggesting that stock buffering is one option to reduce risk. With the uncertainty of supply chain threats, such as climate change, it is important for supply managers at the manufacturer and retail level to assess, monitor, and mitigate the degree of risk across their purchase categories.

Risk as a construct compensates for the inherent uncertainties of decision-making by replacing it with probabilistic assessment especially where there are events requiring control, but it is unclear as to the success of any interventions (Rothstein et al., 2006). The theory of risk colonization, this narrative supports, asserts that there is dynamic coupling of societal and institutional risks that can mean that the role of the state and the role of the market can be fluid. Therefore, it can be postulated that while the issue of sustainability has historically been considered as a societal risk, by instead “rebranding” climate change as an institutional risk, the belief can be promoted that sustainability can actually be managed and mitigated through an institutional proceduralization approach of risk assessment and then a formalized risk management process that enables an adequate risk response.

Resilience as an entity has been said to be the inverse of vulnerability (Folke, 2006; Levina & Tirpak, 2006), the ability to return or rebound to a steady state (Morecroft et al., 2012; Holling, 1996; Pimm, 1991) or the capacity for change, growth, and renewal (Manning & Soon, 2016b). Multiple factors can cause supply chain shocks to occur and thresholds/trigger points will vary for each factor. Thus what is considered as resilience in the supply chain is dynamic and changeable. Indeed Macfadyen et al. (2015, p. 4) asserted that to increase resilience of production and supply:

stakeholders should encourage, and in some cases mandate, sustainable practices with an emphasis on co-ordination at the landscape-scale.

Tendall et al. (2015) considered resilience and sustainability as complementary concepts with resilience being the capacity over time to face short-term disturbances and sustainability as the capacity to preserve the system in the long-term. Building on other literature, Tendall et al. (2015) proposed four elements of a food system resilience action cycle: robustness, redundancy or substitutability, flexibility or recoverability, and resourcefulness or adaptability. This interaction between what is deemed resilience and the notion of sustainability is of importance and this has led to the conceptualization of *panarchy* (Gunderson & Holling, 2002) namely that resilience, especially ecological resilience, involves multiple interactions that operate at a range of levels and thresholds exist that will trigger feedback systems. Berkes and Ross (2016) described panarchy as a concept of nested relationships whereby resilience is influenced by processes that operate on an interlevel and intralevel bases, that is, horizontally or vertically. This means that panarchy in terms of supply chain resilience is influenced by top-down, bottom-up, and/or peer-to-peer relationships. Berkes and Ross (2016:191) concluded that:

As part of a resilience analysis, the concept of panarchy provides an integrative approach for understanding the linkages and dynamics within and across levels of social-ecological systems, in a way that is useful for integrated policy understanding and interventions.

The concept of panarchy as opposed to top-down hierarchy system approaches as proposed by Macfadyen et al. (2015) is thus of interest when considering supply chain resilience, that is, to consider the linkages and dynamics that influence the supply chain and the economical, social, and cultural factors at play, economic and social power being one such element, but there are others worthy of consideration. Thus uncertainty and risk go hand in hand and globalism drives increased focus on the forms of governance required to mediate such uncertainty. Others might consider these thick intersects as supply chain or supply network “hot spots.” A hot spot can be defined as a unit process or phase of a product life cycle that has a potentially significant environmental or social impact (Hyatt & Spicer, 2012). Thus through extension, governance hot spots can be said to be a step, stage, or process within a product life cycle that has a potentially significant sustainability impact and thus appropriate governance controls need to be in place to mitigate such impact. Bienge et al. (2009) described sustainability hot spot analysis (SHSA) as a qualitative approach based on stakeholder involvement to integrate social and environmental dimensions along the entire value chain and to identify the relevant aspects for a product-specific

sustainability management. This type of approach has value in mitigating risk and driving resilience in a given supply chain and also at the product life cycle level and is worthy of more empirical research.

In drawing from the work of [Keohane and Nye \(2000\)](#), it can be argued that sustainability as a concept may well have originated as a baffle for the impact of the complex interdependence of globalism in terms of it creating multiple channels between societies, with multiple actors and multiple issues. Mechanisms to mediate the level of complexity and uncertainty in supply chains are of value in that they help to create a perception of an organization seemingly creating an environment of control and mastery over potential chaos. This dilemma of complexity on the one hand and simplicity of communication and information flow to multiple stakeholders on the other gives rise to the notion of transparency, that is, for organizations to take their complex networks of activity and explain what they do, the impact of their activities and their mechanisms of risk mitigation to a disparate range of stakeholders each with different needs and expectations. Thus transparency refers both to the access of stakeholders to information about the organization's past, current, and planned corporate social responsibility (CSR) activities, and also to whether or not the information presented is balanced, rather than biased ([Basu & Palazzo, 2008](#) cited by [Mazutis & Slawinski, 2015](#)). Further, as societal norms evolve, so do pressures on companies and as a result some organizations will develop a strategy of mimicking what they believe are successful competitors ([de Villiers et al., 2014](#)) or successful best practice.

Isomorphism can be described as a construct that helps to contextualize why organizations that operate within the same socioeconomic environment often behave and communicate in similar ways. Isomorphism creates and spreads a common set of values, norms, and rules that lead to similar practices and organizational structures in a similar field ([Othman et al., 2009](#)). [Czinkota et al. \(2014\)](#) asserted that isomorphism is driven by a need to conform not only to the external environment, but also the context of the environment itself promotes new “rational myths” such as institutionalized rules, norms, and procedural ceremonies. These can be formal or informal. Thus organizations tend to imitate the behavior and actions of similar and/or high-performing organizations ([Othman et al., 2009](#)). Isomorphism enhances companies’ stability and survival, facilitating political power, and institutional legitimacy ([Martínez-Ferrero & García-Sánchez, 2016](#); citing [DiMaggio & Powell, 1983](#)). This means that organizations in attempting to mimic others are seeking to

emulate either their success or their level of legitimacy (Amran & Haniffa, 2011). Isomorphism as a continuous and mutual adaptation (Czinkota et al., 2014) can develop as a result of singular elements, or a combination of three elements, that Joseph and Taplin (2012) argue operate in an integrated way:

- *Normative elements* (normative isomorphism): control of resources including knowledge which drives a common set of norms and morals;
- *Regulatory elements* (coercive isomorphism): existing laws, regulations, and rules that reduce diversity—this can operate at the national, regional, or global level; and
- *Cognitive elements* (cognitive or mimetic isomorphism): social beliefs and cultural meaning that becomes more homologous, accepted corporate behavior especially through benchmarking accepted measures of sustainability and common corporate social performance (CSP) metrics (see Joseph & Taplin, 2012; Czinkota et al., 2014; de Villiers et al., 2014; Martínez-Ferrero & García-Sánchez, 2016).

Keohane and Nye (2000) considered also the concept of isomorphism in terms of the imitation of one society's practices and institutions by another and how it impacts on the construct of society whether political, culture, or personal identity. This suggests that while national norms may exist global norms can develop which can in certain contexts supersede national or regional norms. The process of isomorphism can be as a result of either *consonance*, that is, the situation where corporate and supply chain actors identify mutually shared language and emotions/passions, or alternatively *resonance* which can be described as the process of relational evolution whereby actors create opportunities to reach common goals (Czinkota et al., 2014 citing Barile, 2006; Golinelli, 2010). There is also a herd effect whereby discretionary disclosure is influenced by what others operating in the same field are also prepared to disclose (Dobler, 2008). Convergence tends to commence when companies respond to uncertainty by copying others, that is, mimetic isomorphism (de Villiers et al., 2014). Conversely the opposite of isomorphism and convergence, distinctiveness, is expressed in a variety of ways including being “true to oneself” and developing a differentiated sense of self (Mazutis & Slawinski, 2015, p. 141). Corporate authenticity is about being differentiated, connected, unique, and original (Mazutis & Slawinski, 2015) and such distinctiveness can link to competitive advantage. Stakeholder pressure, coupled with an increasing acceptance of the use of CSP metrics and disclosure frameworks (such as the global reporting initiative (GRI)), encourages more companies to undertake sustainability disclosure

and mimetic isomorphism through benchmarking processes (de Villiers et al., 2014). Within this context of globalism, globalization, resilience, and risk and the process of isomorphism, the scope of mandatory and voluntary sustainability requirements is continually evolving as is the expectation for transparency, integrity, and demonstration of multiple stakeholder value. This chapter will now turn to thoughts of corporate integrity and how it is contextualized.

3 Integrity in the Supply Chain

The Elliott Review (2014) that focused on the integrity and assurance of food supply networks, produced as a result of the horse meat incident in 2013, determined that food integrity was not only concerned with the nature, substance and quality, and safety of food, but also captured other aspects of food production such as “the way it has been sourced, procured, and distributed and being honest about those areas to consumers.” Thus food integrity as a research area has legal, moral, and ethical dimensions (Manning, 2017a). There is an emerging literature in the area of food and supply chain integrity and a plurality of definitions and discourses. Manning (2016) proposed that integrity can be differentiated into the following:

- (1) *product integrity* in terms of innate intrinsic characteristics of the product;
- (2) *process integrity*, that is, the extrinsic characteristics of the product;
- (3) *people integrity* associated with the ethics or behavior of individuals compared with what would be expected, and
- (4) *data integrity* in relation to the data and information that accompanies the food item throughout the supply chain (see also Bouzembrak & Marvin, 2016; PAS 96:, 2014; Spink & Moyer, 2011a, 2011b).

PWC (2008) defined *supply chain integrity* as being concerned with balancing operational objectives with reputational risk in what is often a turbulent business environment. PWC (2008:14) differentiated further between: *operational integrity*, that is, the ability of the supply chain to meet objectives for quality, operations (productivity), and financial (economic) performance and *reputational integrity* as the ability of the supply chain to protect and enhance the brand, manage, and respond to customer and investor concerns, and comply with the growing burden of legislation, for example, with regard to social and labor, environment, and ethics. PWC (2008) suggests that the best sources of

information that demonstrate performance against these criteria reside within the supply chain itself. The PWC definition of integrity aligns with other notions within the literature that reflect supply chain *resilience* (Manning & Soon, 2016b) as well as sustainability (Manning & Soon, 2016a). Thus it could be asserted that food integrity, resilience, and sustainability are interrelated concepts and are often interposed. This multiplicity of vocabulary at the trading level can cause both confusion and also create a lack of clarity in thinking and systems development when organizations seek to address multiple stakeholder requirements to deliver what for some are distinct criteria and for others overlapping in terms of definition.

4 Information in the Supply Chain and Disclosure

Sustainability information has been said to encompass the TBL, the three P's of profit—economic information (profit), people-orientated information, and planet, that is, information associated with environmental impact (Wognum et al., 2011). Sustainability information can firstly be held privately at the organizational level, held within one department, or be part of an intraorganizational information exchange. Secondly sustainability information can be subject to interorganizational exchange and shared by those who have contractual arrangements within the supply chain and still remain private as in the information flow in traditional procurement arrangements, or thirdly information can be made public in some way to a range of supply chain stakeholders that have an interest in the organization. The latter type of information exchange can be through a range of media including annual reports, CSR initiatives, or other forms of communication. Information management frameworks are required to support information flow, transparency, and effective decision-making (Folinas et al., 2006). Thus *transparency* as a construct arises from the desire of supply chain stakeholders to be in a position to make informed decisions and also that they make those decisions on the basis of the information that is provided (Dingwerth & Eichinger, 2010). Transparency is not an ethical principle in itself, but a proethical condition for enabling or impairing other ethical practices or principles (Turilli & Floridi, 2009, p. 105). Turilli and Floridi (2009) determined transparency in terms of information visibility and access, which is increased by reducing or eliminating obstacles. Mol (2015) explained food systems transparency as the disclosure of information, previously

held privately by public and/or private organizations, and states that transparency encompasses quality and sustainability characteristics in order to increase public accountability. Supply chain transparency is the extent to which information is shared, that is, disclosed between supply chain stakeholders without loss, noise, delay, or distortion (Wognum et al., 2011 citing Hofstede et al., 2004; Beulens et al., 2005). This proposes that information disclosed to others has innate characteristics in terms of both quality and quantity. The quality of information influences organizational and supply chain agility and the ability to be responsive (Zhou et al., 2014). It has been argued that supply chain transparency is inconsistently defined and individual scholars tend to focus solely on just one of the many dimensions of transparency leading to limited and often dualistic framings of supply chain transparency, with companies being claimed to be either transparent or nontransparent (Egels-Zandén et al., 2015). Kassahun et al. (2016) citing Moe, 1998; Bertolini et al., 2006; Gandino et al., 2009; Bosona & Gebresenbet, 2013) suggested that a transparency system can be internal (managing data within facilities) or alternatively external sharing data with other supply chain stakeholders and is underpinned by mandatory requirements. Transparency empowers information users to exert influence on disclosers and is a tool for holding powerful actors accountable (Dingwerth & Eichinger, 2010).

Information provides context or meaning as an intrinsic element of its communicative quality. The process of information development requires data to be interpreted and explained by one stakeholder in order for another stakeholder to determine its relevance and significance not only to themselves, but also for the plurality of stakeholders in the supply chain. This interpretation process has ethical dimensions in terms of what to disclose or not disclose, what to assume or not and the emphasis to draw from the material provided at the supply chain level. This requires trust within the supply chain and demonstrates the challenge of consistently demonstrating transparency and suggestions that the process of interpretation is open to malpractice or fraudulent behavior. Thus transparency as an attribute relates to the inherent characteristics of the data and/or information itself, that is, it must be relevant, accurate, factual, reliable, timely, and representative (available in an appropriate quantity) and it must translate into information that is meaningful (Wognum et al., 2011 citing Hofstede et al., 2004). The characteristics of the data and the process of translation into distinct disclosure activities influence the extent to which stakeholders believe that an organization has been open and transparent.

Zahra et al. (2007) describe fraud in itself as the deliberate actions taken by management at any level to deceive, con, swindle, or cheat investors or other key stakeholders and state that fraud can encompass intentional acts such as embezzlement, insider trading, self-dealing, lying about facts, intentional misrepresentations, corruption, cover-ups, and failure to disclose facts. Thus fraud, more generally covers a wide range of activities that could arise in the supply chain including deliberate actions by management to deceive through the use of “disclosure” activities. This type of fraud sits within a wider manifest of dishonest activity which may be concerted or mutually exclusive in the extent of its activity. Food fraud is multifaceted and by nature complex (Manning, 2016). As outlined earlier in this chapter integrity, or lack of it, can take many forms not only with regard to product, process, and data integrity, but also with regard to people integrity. Food-associated fraud, and wider criminal activity, can particularly impact human health and erodes consumer trust (Elliott Review, 2014; Johnson, 2014; Manning & Soon, 2014; PAS 96, 2014; Spink et al., 2015). As an activity, fraud can be differentiated by its impact on individual, multiple, internal, and external supply chain stakeholders and demands for greater transparency could be seen as a strategy to reduce fraudulent behavior. As a result there are increasing mandatory and voluntary stakeholder demands for transparency and the disclosure of information along added value chains (Mol, 2015). Again, this leads to reflection on the characteristics that define the perceived quality of any information that is disclosed. In essence, it could be said that information is data encapsulated in meaning.

Hermanowicz (2008) stated that the meaning of sustainability has changed over time arguing that “originally, sustainability simply meant meeting human demands by natural supplies.” As population grew and issues such as pollution and utilization of resources became more nuanced so did the meaning of sustainability. People prefer certain *objects* because they believe these objects contribute to the achievement of their goals and values and in this context sustainability can be determined as being an object upon which corporate goals and values are laid (Coolen & Ozaki, 2004). Coolen and Ozaki (2004) citing Rapoport (1988) articulate that meaning is an important construct that links people to their environments and as a result meaning is the most important element of the perception of derived function. Translating Rapoport’s (1988) three levels of meaning from their original subject area to the consideration of sustainability in supply chains suggests that:

- *High-level meanings* are related to world views, philosophical systems, and notions such as climate change, greenhouse

gas emissions, water and carbon footprint, biodiversity, and so forth;

- *Middle-level meanings* convey latent functions such as identity, status, wealth, power, that is, expression of identity through purchase of differentiated food products in terms of extrinsic product characteristics, for example, organic food, free-range livestock products, FairTrade, ethical trade, and so on;
- *Lower-level meanings*, that is, everyday and instrumental meanings, such as utility, price, and so forth often called manifest functions.

Thus meaning will drive stakeholders' perception of organizational performance in terms of product characteristics, notions of sustainability, and also how transparent organizations actually are. Laszlo (2008) argued that companies and brands will be successful only if they are genuinely values-led and take a holistic rather than silo approach to the TBL. Therefore holistic innovation and differentiation leads to competitive advantage. Fearné et al. (2012) considered that Porter and Kramer's (2011) "shared value creation" concept suggests that value that is mutually beneficial to both the value chain and society reflects a number of trends in strategic management and value chain research. Indeed, MNCs have taken this approach and continue to take this approach to reverse isomorphism and to differentiate and create their own protocols and procedures around the sustainability of their own supply chains to add value.

Beretta and Bozzolan (2004) identified that the quality of information disclosure depends, first, on the quantity of information released and secondly on the degree of "richness" offered by additional information. Thus the attributes associated with disclosure can include the quantity of information, the density of information in terms of content richness, and whether the information provided is perceived as being positive, neutral, or negative by the target audience, that is, that perceived meaning adds to, or detracts from, the richness of the dialogue. Abraham and Shrives (2014) outlined that attempts to determine the quantity of disclosed information have led to quantity being measured in terms of quantitative analysis of words or statements included in forms of disclosure communication or alternatively by the use of a form of disclosure checklist whereas quality has been determined in terms of the degree of descriptive or qualitative disclosure. Disclosure of sustainability information to supply chain stakeholders can be in terms of financial, environmental, and food safety concerns (Beretta & Bozzolan, 2004; Dobler, 2008; Cong & Freedman, 2011; Abraham & Shrives, 2014) although wider social

concerns are also often included within the scope of sustainability disclosure. Abraham and Shrides determined that disclosed information must be relevant (company specific), current (regularly updated), and authentic rather than being symbolic; and these factors will influence the degree of or meaning associated with the information.

Credibility is an inherent problem in the event of nonverifiable, and discretionary rather than mandatory disclosure (Dobler, 2008). When information is nonverifiable or the verification cost prohibitive, individuals can misreport and misrepresent and Dobler (2008) described this as a “cheap talk” model that threatens credibility. Further Cong and Freedman (2011) citing Clarkson et al. (2004, 2008) argue that organizations who believe themselves to be performing strongly with regard to a certain sustainability attribute are more likely to disclose information because it cannot be easily mimicked by poorly performing competitors. The value to poorly performing competitors of mimicking information in their disclosures is that they can signal that their risk management systems are equivalent to the industry standard (Abraham & Shrides, 2014, p. 93) and this form of isomorphism can be either formal or informal in nature. Alternatively, public disclosure of information may be as a result of an organizational strategy to legitimize the organization in terms of stakeholder expectations and to relieve either private or public pressure on the company (Cong & Freedman, 2011). Legitimacy can be described as the degree of cultural support for an organization and is a state that reflects the degree of perceived organizational concordance, consonance, compliance, its cultural alignment, and the extent of normative support with relevant rules or laws (Meyer & Scott, 1983; Scott, 1995; cited by Czinkota et al., 2014). Palazzo and Scherer (2006) argued that CSR discourse builds on notions of organizational legitimacy, which can be differentiated in terms of cognitive and pragmatic legitimacy in terms of compliance with legislation and also societal expectations and rhetoric. While capitalism is credited with propelling the success of many economies, repeated instances of corporate wrongdoing fuel a deep distrust in the corporation and perceptions of its legitimacy (Rayman-Bacchus, 2006, p. 323). Rayman-Bacchus (2006, p. 330) highlights the challenge for organizations in that:

Boundaries of legitimacy are blurred and corporations may find themselves negotiating that boundary, or actively attempting to redefine the boundary, in terms of changing constituency understanding and acceptance of their actions.

This means that how and what is communicated by organizations will influence their perceived legitimacy. The information provided may or may not reflect the actual performance and organizations may also choose to be selective or ambiguous when disclosing voluntary information.

Baldassarre and Campo (2016) distinguished between transparency and two other characteristics of information namely opacity and translucency. Transparency of a system is determined by the degree of knowledge of the system elements and so a high-level of opacity hampers supply chain flexibility (Winkler, 2009). Opacity is the opposite of transparency and can be said to be a lack of credible information or information asymmetry and the greater the degree of opacity the greater the level of systemic risk (Kozubovska, *in press*). Kozubovska (*in press*, p. 8) argued that organizations (in this case banks) encourage opacity to serve “their own selfish needs” and indeed that opacity is a conscious response mechanism used to provide secrecy to investors and/or to disguise excessive risk taking, especially with regard to long-term risk where investors and shareholders can move on having benefitted from short-term profitability well before long-term risk is realized. Opacity, therefore, is one of a headline set of resilience indicators that also include: management commitment, culture, awareness, preparedness, and flexibility (Bukowski & Feliks, 2012). Thus, opaque companies seek to appear responsible rather than actually applying sustainability principles to their activities (Baldassarre & Campo, 2016). Lamming et al. (2001) suggest that there is a spectrum between transparency and opacity proposing that organizations can work in a form of corporate “hinterland,” that is, there can be degrees of translucency in terms of information and data exchange with both internal and external stakeholders. Therefore, it can be postulated that communication exchanges can, depending on the nature of the stakeholder, exist on a spectrum of translucency or ambiguity. There is a strategic reason for this because full supply chain visibility requires open sharing of accurate and timely information between internal and external stakeholders (Bartlett et al., 2007). This could lead to corporate vulnerability in terms of competitors gaining knowledge of products and processes and an understanding of the intrinsic weaknesses of the organization and the associated chain. Thus degrees, or levels, of supply chain visibility are created on the basis of the nature of the knowledge seeker and the knowledge recipient. This is driven through notions of self-preservation and maintaining business value in the face of the existence of information that could potentially cause damage to the organization. However, if organizations are

seen as withholding information this will reduce the level of trust for both internal and external stakeholders. This applies to the concept of translucency, that is, a differential visibility of the organization's data and information based on the nature of the stakeholder. Further, if data that is being reported is historic and does not reflect current practice this could mean that employees feel it would be appropriate, and of value to the organization, to report to a different level of translucency than perhaps what external stakeholders would expect.

Strategic ambiguity can be described as those instances where individuals either as themselves or on behalf of corporations purposefully use ambiguity to accomplish defined goals (adapted from Eisenberg, 1984). This approach can suggest a unified diversity, that is, through ambiguity all multiple viewpoints are met, and approaches can often be flexible as long as the ultimate goal is reached. Strategic ambiguity can be a response to uncertainty, a desire to remain unconstrained in the future or as a response to the political nature of collective action (Alesina & Cukierman, 1990; Glazer, 1990; Aragonés & Neeman, 2000; Meirowitz, 2005; Jarzabkowski et al., 2010). Therefore, strategic ambiguity allows multiple perspectives and objectives to coexist especially in a situation where what is believed to be true is fluid, uncertain, or where different groups may have a different definition of what they believe to be true (Leitch & Davenport, 2007). Corporate ambiguity has three dimensions: Goal ambiguity (as a result of plurality of interests), authority ambiguity (diffuse sources of power), and technology ambiguity (Jarzabkowski et al., 2010 citing Cohen & March, 1986). Technology ambiguity can be described as the sometimes opaque relationship between corporate goals, that is, the strategic framework for the organization and the operational tactics of delivery in terms of resources, performance management, or the interaction between strategic and operational objectives (Jarzabkowski et al., 2010). Therefore, a series of operational objectives can be designed to work at single chain or actor levels in the complexity of a wider food supply chain that can then through a mutually concerted process deliver the overarching strategic objective, for example, to reduce waste in the supply chain or influence the carbon footprint of a food product on a retail shelf. Sim and Fernando (2010) argued that strategic ambiguity can be used for four reasons: promoting unified diversity, preserving privileged positions, promoting deniability, and facilitating organizational change (see Manning, forthcoming, 2017b). Strategically ambiguous messages can engender diverse interpretations between varied audience segments that ultimately translate into a relatively uniform positive

corporate image (Smith et al., 2006). Sim and Fernando (2010) asserted that the influence of strategic ambiguity on both organizational strategy making and communication may lead to a challenge of unethical executive behavior and action (Manning, forthcoming, 2017b). Indeed, external disclosure of company information may be influenced by a reluctance to provide information that is commercially sensitive, or where others could use the information to harm the organization's interests (Abraham & Shrives, 2014).

This business context gives rise to notions of greenwashing or greenhushing and a questioning of supply chain ethics. Delmas and Burbano (2011) asserted that increasing numbers of organizations, whether intentionally or unintentionally, are engaging in greenwashing through their publications and discourse and misleading consumers about the organization's environmental performance or the environmental benefits of a product or service. Greenwashing has been described as follows:

- the tendency of a company to beautify its image through communication that emphasizes positive achievements and conceals negative conduct often to drive transient image improvement (Baldassarre & Campo, 2016); or
- the selective disclosure of positive information about an organization's environmental or social performance, without full disclosure of negative information on these dimensions, so as to create an overly positive corporate image (Lyon & Maxwell, 2011), and
- a strategic action in that it may mislead stakeholders about an organization's actual social performance (Roulet & Touboul, 2015).

Organizations that focus on CSR activities that "only benefit themselves are also more likely to engage in greenwashing" (Mazutis & Slawinski, 2015, p. 145). Marquis et al. (2016) suggested that unless corporations are actively monitored by their stakeholders, they will avoid disclosing information that gives a negative impression of their overall business performance. Thus, as organizations are encouraged through global norms of increased corporate accountability to communicate on their sustainability performance, as Marquis et al. (2016) pose, is the increased volume of information an actual demonstration of increased corporate transparency or merely a symbolic action? Further, preference is given by organizations to communicating what is easy, and not what is important (Smith & Font, 2015).

Greenhushing is where corporations, as a result of a low moral intensity, mask the potentially negative consequences of weak performance to protect their business, especially from consumers

who may interpret their statements as hypocritical (Font et al., 2017). The distance between corporate disclosure and actual corporate performance, especially in terms of objectively quantifying CSP as part of a wider CSR strategy, is reviewed by Font et al. (2012). CSP can be measured either as an aggregate metric (for a number of submeasures) or in terms of performance against each of the individual components. Thus greenhushing can occur when an organization implements a form of trade-off by focusing on one CSP parameter that paints the organization in a good light while failing to report CSP in an area where the reverse is the case (Manning, forthcoming, 2017b). Martens (2008) differentiated between greenwashing, greenhushing, and “green telling,” the latter focusing on the brand value associated with green credentials. Martens argued that greenhushing might be a reaction to the concern of a corporation that it might be seen as greenwashing so that it hides its green credentials to avoid confusion. Therefore, social self-disclosure or the use of soft management claims is a strong context in which strategic ambiguity or greenwashing can take place as self-disclosure may not actually relate to real organizational performance (Manning, forthcoming, 2017b). Hard self-disclosure is normative, that is, relating to objective measures whereas soft self-disclosure can be said to be descriptive, management claims (see Chen & Delmas, 2011; Moroney et al., 2011; Carroll & Shabana, 2010). The use of metrics in CSP is discussed in more detail later in this chapter.

5 Transparency in the Food Supply Chain and the Role of Disclosure

Transparency in the food supply chain is based primarily on the visibility of the production processes associated with the food product for all stakeholders and secondly that stakeholders are able to understand or quantify how these processes affect the extrinsic sustainability characteristics of the product such as environmental protocols and procedures or animal welfare standards (Blokhuis et al., 2003; Manning, 2017a). Disclosure of information to consumers about sustainability can take two basic forms:

1. *Explaining supply chain activities* in an effort to reduce value chain complexity and the media through which information is communicated to consumers, and
2. *Introducing labeling and certification systems* that communicate from the packaging or associated media compliance with a standard developed to determine the degree of sustainability of a given organization in the supply chain (Mol, 2014).

Trust has a crucial role in situations characterized by risk and uncertainty (Hartmann et al., 2015). Further trust reduces complexity, thus acting as a cue in consumer decision-making processes (Hartmann et al., 2015 citing Savadori et al., 2010). Sustainability labels allow consumers, when making food choices, to consider visual cues that relate to environmental and ethical considerations, otherwise more indirect inferences are drawn from other product characteristics such as country of origin or provenance (Grunert et al., 2014). Sustainable products can as a result accrue value if individual or collective product or process differentiation drives marketing and brand development (Manning, 2015). Demonstration of such attributes or characteristics implies the requirement within the supply chain to create mechanisms to deliver transparency, since consumers have to believe, and by inference, organizations have to demonstrate, that the often higher prices demanded are justified by the measures employed to improve what is determined as “sustainability” (Wognum et al., 2011). Hartmann et al. (2015) citing the work of Rousseau et al., 1998; Castaldo et al., 2009; Bachmann & Inkpen, 2011; Welter, 2012), differentiated between levels of trust and typologies of trust including:

- *Micro-level trust* (interaction-based or relational-based trust based on personal experience between two actors),
- *Meso-level trust* and
- *Macro-level trust* (institutional-based trust based on formal governance controls such as legislation, certification, or informal governance controls such as corporate reputation or community norms).

Transparency around sustainability is assessed not only against normative criteria related to power, democracy, participation, accountability, and right to know, but also as a process of reducing information asymmetries, and ensuring more effective environmental governance (Mol, 2014). Dingwerth and Eichinger (2010) argued that as transparency is linked to personal autonomy, transparency in itself becomes “a normatively loaded term,” that is, has innate meaning, and requires organizations to completely disclose all information that stakeholders need to make an informed decision to buy or not to buy, to invest or not to invest, or to collectively organize against a company or refrain from doing so. It is the ability to create an environment of informed action based on data that makes transparency a different supply chain attribute to the often-used term, traceability. Fig. 1 has been developed to conceptualize the disclosure spectrum which flows from transparency through translucency to opacity. The influence of stakeholder requirements,

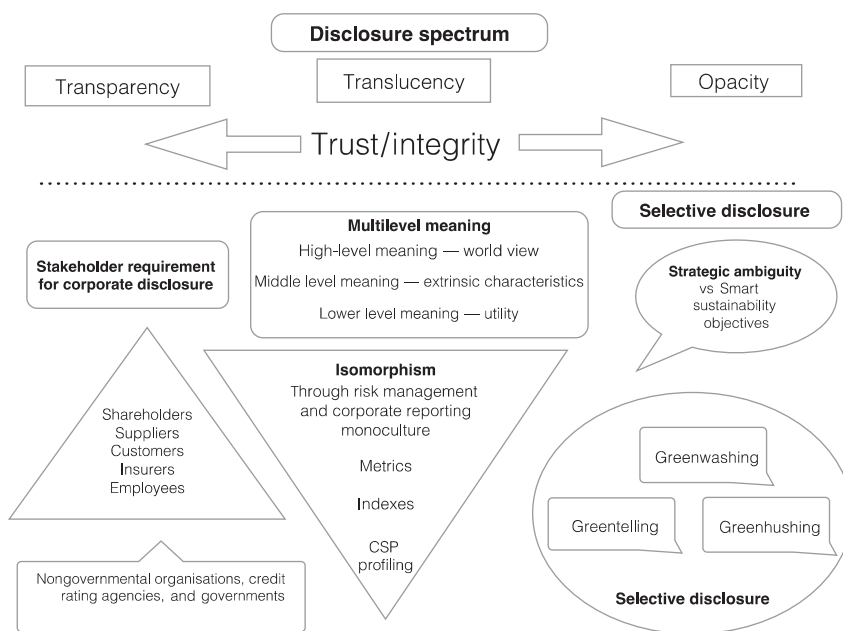


Fig. 1 Disclosure spectrum.

isomorphism and monocultural reporting, that can have single or multilevel meaning and the challenges of selective disclosure are considered.

Forms of value chain traceability were initially related to the development of total quality management systems for whole chains and individual products, logistics management, and verification of product specifications (Mol, 2014). Traceability of a given product and/or its component parts was developed to provide consumers with assurance about the source (provenance) and the safety of food, to also allow for the identification of the source of contaminated or substandard product thus enabling the process of product recall when required, to satisfy the requirements of labeling regulations and assists in plant and animal disease control and medicine and chemical residue monitoring (Leat et al., 1998). Therefore, traceability of a given food and/or its component parts provides consumers with assurance about the source (provenance) and the safety of food, allows for the identification of the source of contaminated or substandard product, satisfies the requirements of labeling regulations and assists in plant and animal disease control and medicine and chemical residue monitoring (Leat et al., 1998 cited by Manning, 2017b). Holistically, traceability encompasses the wider

notions of food integrity and authenticity (Charlebois & Haratifar, 2015). Transactionally, traceability can be said to add value to the product as a process by providing the communication linkage for identifying, verifying, and isolating sources of noncompliance and by enabling supply chain partners to determine and meet product standards and customer expectations (Pizzuti & Mirabelli, 2015). Manning (2017b) outlines that from a traceability viewpoint there are innate requirements in terms of the characteristics of information quality that are required to be able to isolate a food safety problem and minimize the impact of a problem should it arise. These characteristics drive traceability and also underpin notions of information transparency too. They include accessibility, accuracy, adequacy, availability, connectivity, credibility, currency, completeness, frequency, relevance, reliability, and timeliness, (Delone & McLean, 1992; Sum et al., 1995; Seddon, 1997; McCormack, 1998; McGowan, 1998; Petersen, 1999; Chopra & Meindl, 2012; Li et al., 2005; Zhou et al., 2014). Some of these inherent attributes such as accuracy, relevance, reliability, and timeliness have been used to determine transparency as well (Wognum et al., 2011 citing Hofstede et al., 2004). The plurality of definitions in the literature creates challenges when seeking to provide a clear determination of what transparency or traceability are both mutually and also exclusively. Turilli and Floridi (2009) determined that transparency can be said to be described in terms of information visibility and access, which is increased by reducing or eliminating obstacles, thus transparency reflects perceptions of information availability and depends not only on factors such as the availability of information, but also on the context of the information that is made available, that is, voluntarily or not, and in a structured way or reluctantly and whether it is in a format that aids the recipient's decision-making process. It is this consideration of delivering the information in a format that can be readily utilized by multiple stakeholders that underpins transparency or conversely gives rise to what is deemed as accepted or shunned corporate practices.

Ventriloquism can be described as mobilizing an entity to “speak for you” (Jönsson, 2014 citing Cooren, 2000). Thus, the employee, as the actor, contributes to trust in their organization through their conduct, that is, they animate the business by their agency using an “infrastructure of action.” This infrastructure of action includes a framework characterized by business environment, rules, and vocabulary. Ventriloquism is a recurring feature of a range of contemporary discourse practices (Leppänen, 2015). Corporate ventriloquism (see Jacklin, 2005; Bantjes, 2007;

Leppänen, 2015) is the rhetorical process through which corporations or trade associations transmit messages via a second party (such as a private organization), usually of their own making to front, construct, and energize an alternative public rhetoric, ethos, voice, or identity that advances their corporate interests and develops networks and relationships (Schneider et al., 2016). Corporate ventriloquism drives corporate messaging through employee testimonials, for example, through website case studies, newsletters, blogs, and so on (Maagaard, 2014). Dunsmore and Haspel (2014) argued that the ventriloquization of attributes creates a shift between objective characteristics and socially constructed characteristics, that is, a dialogue can be given the appearance of being objectively focused, for example, science based but instead be socially constructed, that is, perception based. Therefore, strategic ambiguity and corporate ventriloquism are just two examples of where corporate dialogue is suggested to be translucent or opaque. Further to reduce the innate complexity of driving sustainability in the supply chain, using aggregate scoring as a form of greenhushing or alternatively exhibiting mimicry of those organizations that demonstrate best practice, there is an increasing isomorphic coalescence toward standard sustainability benchmarking and metrics in the supply chain.

6 Measuring Sustainability

CSR, or sustainability, indicators can be characterized according to their specific TBL attributes. While CSR is seen as an opportunity to strengthen corporate legitimacy some stakeholders might be skeptical of or distrust CSR disclosures (Bachmann & Ingenhoff, 2016). Rayman-Bacchus (2006) concurred stating that legitimate corporate activity can be contested when differing stakeholders hold conflicting beliefs about the value or morality of such activity. Discretionary CSR disclosures allow organizations to deliver the desired outcomes for stakeholders (instrumental dimension) can be used to treat stakeholders with dignity and respect (relational dimension), and/or demonstrate that organizational actions exceed normative standards in terms of profitability and legal requirements (moral dimension) (Bachmann & Ingenhoff, 2016). Bourlakis et al. (2014) differentiated between four supply chain sustainability indicators (efficiency, flexibility, responsiveness, and product quality) thus integrating rather than differentiating the TBL. Product quality has economic,

environmental impact via potential wastage and social and cultural attributes.

Sustainability indicators can be presented either in a structured framework that isolates and reports on relevant indicators or alternatively such indicators can be aggregated toward a composite index, score, or rating (Dong et al., 2015). The hard approach to CSR, rather than the softer more strategically ambiguous approach, would suggest that sustainability indicators must be *specific* (outcome bound), *quantitative* (measureable), *usable* (of practical value), *available* (data easily collated), *cost effective* (not expensive to collect), and *sensitive* (demonstrate changes in circumstances) as identified by Bell and Morse (2003). This does not preclude the use of qualitative indicators, but by their nature qualitative indications do not readily drive business performance and continuous improvement (Manning & Soon, 2016a). Singh et al. (2009) suggested that normalization and weighting of indicators can show a high-level of arbitrariness, especially where they include both hard and soft criteria and along with aggregation there needs to be appropriate rules that guarantee consistency and meaningfulness of composite indices.

CSP profiling approach can add value by: identifying areas of trade-off and seeking to meet plural perceptions that can provide meaning to multiple stakeholders; ensuring that stakeholders can define their own sustainability standards; and by giving a clear typology of the CSR/sustainability activity undertaken and using hard measures to driving outcome-based assessment that is observable and quantifiable (Mahon & Wartick, 2012). Sustainability metrics have been developed by multiple stakeholders to assess and compare organizations (Antolín-López et al., 2016). CSR/CSP can be measured in many ways in terms of *social self-disclosure* such as through voluntary and/or mandatory reporting and *social performance measurement* by the use of a sustainability framework, composite index third-party ranking systems or league tables (Font et al., 2012; Manning, forthcoming, 2017b). Maintaining shareholder confidence is key for an MNC to ensure continued investment that will sustain business planning and operational activities and past investment risk does not guarantee future investment risk. Jaegar (2006) proposed that the factors that need to be considered to determine investment risk include organizational, market-, and nonmarket-related factors. Credit risk is an important aspect and in capital markets credit ratings will influence investment decisions (Manning et al., 2007); however, although current credit risk rating can be determined that approach alone will not necessarily state which organizations run the risk of defaulting in the future. Antolín-López et al.

(2016) suggested that rating agencies are actually crucial stakeholders because they not only inform investors about organizational financial performance but they now also guide investors in terms of an organization's social responsibility and sustainability performance. Multiple stakeholders, including business academics, executives, and governments, use this data as a means to measure sustainability performance, the organization's record of disclosure and thus provide a measure of transparency.

Dong et al. (2015) considered how sustainability frameworks can assist in the selection of indicators when constructing an index, and suggested that a dynamic and objective process of indicator selection for both frameworks and composite indices should be developed. Sustainability stock indexes such as the Domini 400 Social Index, the Dow Jones Sustainability World Index (DJSI World), or FTSE4GOOD Index can be used as an indicator of CSP although Ziegler and Schröder (2010) considered there are questions about the reliability of this metric. Van Stekelenburg et al. (2015) studied the relationship between CFP and CSP (utilizing the DJSI as a measure) concluding that the market rewards organizations with high CSP in terms of stock returns, although the wider literature gives a mixed view. Antolín-López et al. (2016) analyzed the DJSI confirming that it has:

- thirteen *economic criteria* including criteria related to anti-crime policy measures, corporate governance, bioethics, customer relationship management, innovation management, market opportunities, marketing practices, and price risk management;
- fourteen *social criteria* including criteria addressing human capital development, labor practice indicators, occupational health and safety, stakeholder management, standards for suppliers, and social reporting; and
- eleven *environmental criteria* including criteria on biodiversity, environmental footprint, climate change governance, climate strategy, electricity generation, and environmental reporting.

Antolín-López et al. (2016) reflected that there are substantial differences in the subdimensions covered by different sustainability indices and this could be due to the lack of consensus on what corporate sustainability is and the scope of each element is. CSP reporting also contains a trade-off between positive and negative indicators of performance for the same organization (Chen & Delmas, 2011). Chen and Delmas (2011) argued that the multidimensionality of the CSP construct is the primary difficulty in measuring CSP and this plurality of factors cannot be aggregated easily into a single overarching, or headline, measure. Further, a

single measure may not allow for sufficient clarity on the distance between those organizations that are promoting social responsibility and those who are not; thus the use of multiple measures has developed in these frameworks.

The sustainability indexes seek to contextualize and measure supply chain risk across the TBL. Sridhar and Jones (2013, p. 92) argued that rather than regulating corporations, “the TBL is a method of pushing social problems and pressures towards economics and changing corporate behavior through institutional pressure and self-regulation.” This underpins that isomorphism through the utilization of the TBL encapsulates as previously described elements of mimicry, coercive market measures, and normative standards. Rothstein et al.’s theory of risk colonization asserts that there is dynamic coupling of societal and institutional risks, which means that the role of the state and the role of the market is fluid. While sustainability indicators and metrics link to the TBL evolved thinking emphasized the need for system thinking “rather than the reductionist concept” of sustainability pillars and by inference indices and integrated indicators which can be of limited nature as they fail to account for complex system characteristics, including system dynamics, interconnections, and interdependencies of system components (Gamage et al., 2013), suggesting that sustainability indices have a role to play in mediating the process of disclosure. However sustainability indices drive isomorphism so that the communication process is uniform and thus is easier to navigate by external stakeholders such as investors, banks, and so forth. However, conversely the indices have little value in driving integrated operational approaches for sustainability in the supply chain.

7 Conclusion

Sustainability as a construct is continually evolving especially where the scope of mandatory and voluntary requirements changes and realigns. This chapter has explored the narrative of sustainability and CSR in the food supply chain. The construct of sustainability is plural which gives fuel to the notion that organizations opt for selective disclosure, strategic ambiguity, greenwashing, and greenhushing to paint a favorable company image. The concept of panarchy, as opposed to the use of top-down hierarchical systems, and holistic rather than prescriptive approaches to improve sustainability that increase resilience and mitigate supply chain risk have been discussed in this chapter. This holistic approach extends far beyond the risk rating and

risk analysis approach of using sustainability indices. Chaffin and Gunderson (2016) concluded that when considering adaptive governance the theories of panarchy illustrate that social and ecological processes interact in ways that can not only lead to a shift in environmental outcomes, but also to changes in governance approaches or to the retention of prior policies, rules, processes, and institutions. It is important to note that this discussion of adaptive governance and panarchy only includes two of the three elements of the TBL, promoting questioning of whether adaptive governance at the food supply chain level is actually compatible with the notion of the TBL. Panarchy as a concept recognizes a series of nested relationships whereby resilience is influenced by processes that operate on an interlevel and intralevel basis, that is, horizontally or vertically. Thus developing adaptive governance of sustainability to underpin resilience at the supply chain level requires an integrative panarchical approach (Berkes & Ross, 2016) that recognizes the linkages and dynamics within and across the system. Governance hot spots have been described here as a step, stage, or process within a product life cycle that has a potentially significant sustainability impact and thus appropriate governance controls need to be in place. Governance hot spots will be supply chain specific in terms of product, processes, and stakeholders that are of influence. This hot spot approach is one of mitigating risk through a bottom-up approach rather than the hierarchical approach of top-down sustainability indices. It requires ownership of resilience and sustainable business to sit at an operational rather than a strategic level. Therefore, the key to effective benchmarking is to determine whether the process will be undertaken at a strategic management level to address an overall supply chain target, for example, reducing waste as a proportion of the product sold at the retail level or undertaken at a specific business or at a subbusiness activity/enterprise level (Manning et al., 2007). A series of operational objectives can therefore be designed to work at single levels in the supply chain that through a mutually concerted process deliver the overarching strategic objective (Manning & Soon, 2016a).

Manning and Soon (2016a) determined that TBL metrics can only be developed after the strategic: operational interface has been considered and decisions made as to the underpinning objectives of the benchmarking approach.

Reflection on the content of this chapter leads to consideration of the concept of meaningful disclosure especially where the audience has multiple concepts of meaning. The argument has been put forward that where there is multiplicity of vocabulary at the trading level, this can cause both confusion and also create a lack

of clarity in thinking and systems development when organizations seek to address multiple stakeholder requirements to deliver what for some are distinct criteria and for others are overlapping in terms of definition. Thus context and meaning is crucial when considering definitions of transparency and the degree, quality, and nature, of disclosure of information to supply chain stakeholders. Information providing context or meaning as an intrinsic element of its communicative quality requires data to be interpreted and explained by one stakeholder in order for another stakeholder to determine its relevance and significance not only for themselves, but also for the wider stakeholders in the supply chain. This interpretation process has ethical dimensions in terms of what to disclose or not disclose, what to assume or not and the emphasis to draw from the material provided at the supply chain level. This requires trust within the supply chain and demonstrates the challenge of consistently demonstrating transparency and suggestions that the process of interpretation is open to strategic ambiguity, malpractice, or fraudulent behavior.

Meaning will drive stakeholders' perception of organizational performance in terms of sustainability and transparency and whether an organization uses a holistic rather than silo-based approach to the TBL. Indeed some MNCs have taken and continue to take this approach to reverse isomorphism and to differentiate and create their own protocols and procedures around the sustainability of their own supply chains to add value. This allows for differentiation of their products and their value offering.

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PART

B

SUSTAINABLE FOOD PROCESSING

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ENERGY SAVING FOOD PROCESSING

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1 Introduction

Energy efficiency enhancement is always considered as a challenging issue due to different reasons (e.g., higher greenhouse gas emissions). Three major solutions could be taken into account: firstly, employing more efficient behavior, secondly, utilization of alternative fuels or production/transport/consumption routes that provide the same service while consuming lower energy, and finally replacing some novel technologies instead of the conventional energy-intensive operations (de Mello Santana & Bajay, 2016). The food industry (the fifth biggest consumer of energy in the United States) is among those industries that need to be improved in terms of energy consumption, as a significant amount of machinery and energy is applied in food processes during the conversion of edible raw substances to higher-value food products. Energy efficiency enhancement in the food industry should be evaluated in both technical and financial aspects to be feasible and practical (Wang, 2014).

One of the most energy consuming unit operations used in the food industry is thermal processing including pasteurization, sterilization, dehydration, drying, chilling, and freezing. During these processes in the conventional way, heat is transferred to the food material through convection, conduction, and radiation. By contrast, there are other effective methods of heat transfer effected by implementing novel technologies (Wang, 2014).

Application of these food processing techniques can reduce the energy consumption and consequently decrease the production cost and enhance the sustainability of food production. Generally, emerging technologies are divided into two main categories including: (1) thermal (e.g., ohmic heating (OH)) and (2) nonthermal processing (e.g., high-pressure processing, electrotechnologies, and irradiation). Different mechanisms applied during these methods such as electromagnetic, electric field, and pressurization resulted in better heat transfer than conventional methods (Pereira & Vicente, 2010). In addition to saving energy, most of them also lead to water saving, reliability increment, emissions lowering, better product quality, and productivity enhancement (Masanet et al., 2008).

In this chapter, the principles and mechanisms of several novel thermal and nonthermal technologies for energy saving in food processing are reviewed. Among their different utilization in various food processes, their applications for pasteurization, sterilization, evaporation, dehydration, chilling, and freezing are highlighted. Finally, the benefits and challenges of these novel technologies are introduced and discussed.

2 Energy Consumption for Conventional Processing of Food Products

Energy consumption during the processing of food products is highly dependent on the type of product being processed. For instance, the energy consumption is equal to 9385 MJ for making one ton of milk powder, and 9870 MJ for making 1 ton of whey powder, whereas only 2 MJ of heat are required to produce 1 ton of pasta (Bundschuh & Chen, 2014). In addition to the product properties, many other factors influence the energy consumption in the food industry including the type of equipment, the infrastructure, the ambient temperature, and the skills of the operators.

2.1 Pasteurization and Sterilization

2.1.1 Pasteurization

Pasteurization is considered as one of the main unit operations applied to improve the microbiological quality of a food product. Conventional pasteurization allows the destruction by heat of most of the heat-sensitive microorganisms causing food spoilage but at the same time, it causes the degradation of the sensory and nutritional attributes of the food products. The energy required

for heat during processing depends on the fluid type (specific heat of fluid, C (kJ/kg°C)) and the mass flow (Q_m (kg/s)), the difference between inlet and outlet temperatures ($\Delta\theta$ (°C)), and the time (t (h)) required for pasteurization. This could be determined using

$$W \text{ (kWh)} = P \times t \quad (1)$$

where P (kW) is the consumed power (1 kWh = 3600 J), which could be calculated using

$$P \text{ (kW)} = Q_m \times C \times \Delta\theta \quad (2)$$

To save energy, the heat applied for pasteurization is typically used to warm the cold product. For instance, raw milk is usually heated from a chill temperature (i.e., 4°C) to 72°C for pasteurization for 15 s, before being chilled again to 4°C. The hot product (after pasteurization) is used to warm-up the cold one in counter-current circulation, which leads to precooling the pasteurized product, and preheating the raw one, which helps to save the refrigeration and heating energy. The process takes place in a heat exchanger that is called either regenerative heat exchange or heat recovery (Fig. 1). In most of the cases, this recovery process leads to recycle up to 95% of the heat content of the pasteurized product. Mastering the heat recovery process is of great importance as it allows saving significant quantity of energy. For instance, the steam required for pasteurization could be reduced from 0.012

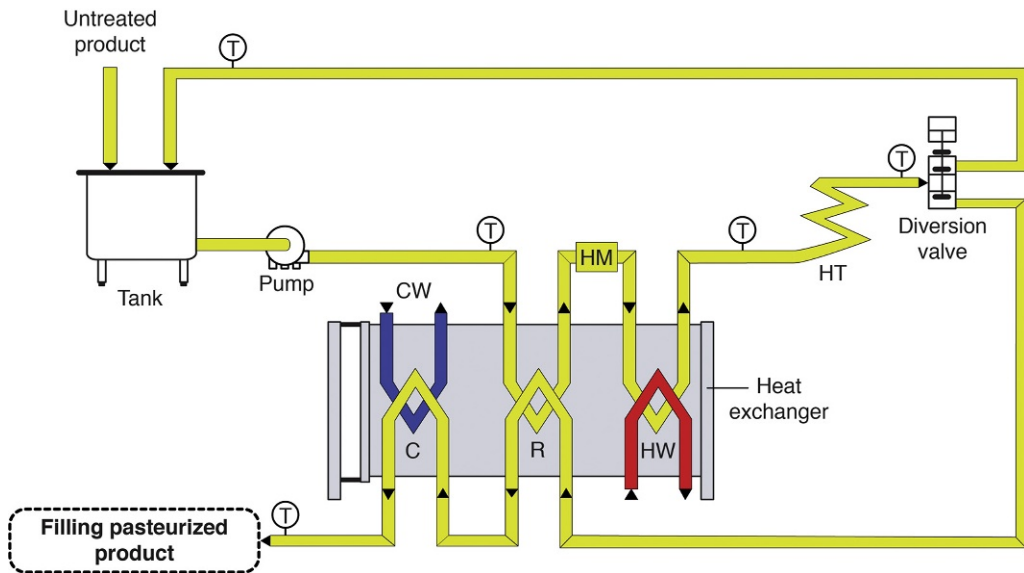


Fig. 1 Diagram of continuous pasteurizer. *C*, cooler; *CW*, cold water; *HM*, homogenizer; *HT*, holding tube; *HW*, hot water; *R*, regenerator.

to 0.003 kg/L of product, when the regeneration percentage increases from 80% to 95%. Although widely used, pasteurization is not able to kill the spore-bearing organisms, such as thermophilic *Bacillus subtilis*, and in many cases, sterilization of the product is required.

2.1.2 Sterilization

When compared to pasteurization, sterilization allows the total destruction of microorganisms present in the food product being processed. In fact, it is able to kill a wide range of microorganisms (yeasts, molds, bacteria), as well as spore formers, allowing thus the storage of the product posttreatment for a long time and at ambient temperature. Conventional sterilization consists of heating the product at high temperature (in general between 110°C and 125°C) for few seconds. This step is followed by equilibration at lower temperature, and finally a cooling step to avoid the overcooking of the product. Although efficient, sterilization leads to the deterioration of the organoleptic properties and the sensory attributes of the food product (Ramesh, 1995). The energy (W) required to produce steam for sterilization is given by

$$W \text{ (kWh)} = m \left(\int_{T_1}^{T_v} C_{Pl} dT + l_v + \int_{T_v}^{T_2} C_{Ps} dT \right) \times \frac{1000}{3600} \quad (3)$$

where m (kg) is the mass of water being heated, T_1 (K) is the initial temperature of water, T_v is the vaporization temperature of water ($=373$ K), T_2 is the final temperature of steam (K), C_{Pl} is the specific heat of water ($=4.18$ kJ/kg K), C_{Ps} is the specific heat of steam ($=1.66$ kJ/kg K), and l_v is the specific enthalpy of vaporization ($=2257$ kJ/kg).

Analyzing the energy consumption required for food sterilization allows: (1) providing quantitative information to design the steam generation and delivery systems, and (2) evaluating the modes of energy loss during the treatment. This analysis of energy consumption could be used to quantify the conservation practices of energy (Steffe et al., 1980). Evaluation of energy consumption required for sterilization has been widely carried out for milk product's processing. Both tube and plate exchangers are used in the food industry for sterilization. The energy consumed for direct sterilization and cooling is relatively high, thus, using regeneration systems, as described above, allows saving substantial quantities of heat. Generally, regeneration efficiencies of up to 90% could be reached using plate heat exchangers (Ramesh, 2007).

2.2 Evaporation and Dehydration

Evaporation and drying operations are usually used in the food industry to concentrate and dry the foodstuffs, respectively. These processes allow reducing the water availability (water activity) and make the growth of microorganisms during storage difficult. The terms dried and dehydrated are not synonymous. In fact, when food product contains more than 2.5% water (dry basis), it is characterized as dehydrated, whereas, when it contains less than 2.5% water (dry basis), it is characterized as dry (Vega-Mercado et al., 2001). Different forms of water are present in food products, particularly free and bound water. Bound water has different properties than pure water and could be defined as unfreezable, immobile, monolayered, and nonsolvent water (Rahman, 1995).

The most common modes of dehydration and drying are well described in the literature, including air drying (Calín-Sánchez et al., 2014), freeze drying (Pei et al., 2013), mechanical dehydration (Praveen Kumar et al., 2005), and osmotic dehydration (Loredo et al., 2011). The conventional method of drying food products is using hot air. In this technique, convection is the mode of heat transfer from gas to the treated product. Drying consumes significant amount of energy and the rate of convective heat transfer could be written as

$$Q(W) = h_c \times S \times (T_s - T_\infty) \quad (4)$$

where h_c (W/m² K) is the convective heat transfer coefficient, S (m²) is the boundary surface area, T_s and T_∞ are the temperatures at the surface and at the bulk fluids, respectively.

An average of 6 MJ is required to remove 1 kg of water from a product. The choice of the heating method is very important to reduce this amount of energy. To reduce the energy cost and improve the quality, numerous drying methods (e.g., electro-technologies, high-pressure processing, microwaves, ultrasound, and pulsed lights (PLs)) have been suggested that will be further detailed in this chapter.

2.3 Chilling and Freezing

The effective control of bacterial activity is one of the key challenges in the food industry. In addition to the methods described above, this control could be performed by decreasing the temperature of the product through chilling under the optimum growth temperature (usually at 4°C), or even freezing, which reduces the water activity and inhibits the growth of microorganisms. The freezing process consumes a huge quantity of energy and one

of the keys to enhance the industrial profitability is to reduce the energy consumption. For instance, to process 1 kg of food product at -20°C , 1.2 MJ is required. The energy (W) required to freeze a food product is given by

$$W \text{ (kWh)} = m \left(\int_{T_1}^{T_0} C_{Pl} dT + H_L + \int_{T_0}^{T_2} C_{Pf} dT \right) \times \frac{1000}{3600} \quad (5)$$

where m (kg) is the mass of the product being frozen; T_1 , T_0 , and T_2 are the initial, freezing, and final temperature of the product ($^{\circ}\text{C}$), respectively; C_{Pl} and C_{Pf} are the specific heat (kJ/kg) of food above and below freezing, respectively; and H_L is the latent heat (kJ/kg).

Mastering the energy loss during the above-mentioned unit operations (pasteurization and sterilization, evaporation and dehydration, chilling and freezing) is of great importance to increase the profitability of the food industry. For instance, increasing the energy efficiency by 1% could result in increasing the profitability of the industry by as much as 10% (Beedie, 1995). Up to the present, numerous novel thermal and nonthermal processing techniques have been developed to replace the conventional thermal processing methods to improve the energy saving in food industry.

3 Novel Thermal and Nonthermal Food Processing Technologies for Energy Saving

3.1 Electrotechnologies

Conventional food processes such as pasteurization, sterilization, evaporation, dehydration, chilling, and freezing are energy consuming. They could be replaced by emerging technologies such as novel thermal and nonthermal processes to reduce energy consumption, production costs, and improve the sustainability of food production. In this line, the use of electrotechnologies, especially pulsed electric fields (PEF), ohmic heating (OH), and high-voltage electrical discharges (HVED) could be a good way to achieve the above-mentioned goals.

3.1.1 Principle and Mechanism of Work

Pulsed Electric Fields

PEF technology has been shown to be promising as an efficient alternative to conventional cell disintegration techniques (Barba et al., 2015; Roohinejad et al., 2014). PEF treatment consists of

an electrical treatment of short time (from nanoseconds to milliseconds) with electric field strength from 100–300 V/cm to 20–80 kV/cm (Koubaa et al., 2015; Vorobiev & Lebovka, 2010). At high electric fields (≥ 20 kV/cm), it can constitute an alternative to traditional thermal processing to inactivate alternative and pathogenic microorganisms and quality related enzymes, with the advantage of retaining sensorial-, nutritional-, and health-promoting attributes of liquid food products (Sánchez-Vega et al., 2015). Under the effect of PEF at low electric fields, the biological membrane is electrically pierced and losses its semipermeability temporarily or permanently, so-called reversible or irreversible electroporation (Deng et al., 2015; Roselló-Soto et al., 2016) (Fig. 2). According to the above-mentioned phenomenon, PEF-treated plant tissue could be characterized by electroporated cell membrane, affected texture, and improved water or solutes diffusion. Therefore, the mechanism of microbial inactivation under PEF could be explained by electroporabilization of microbial cells. In the irreversible type of pore formation, the intercellular components may interact with the extracellular media, which causes organelle damage and the ultimate death of the PEF-treated microbial cells. These changes in the PEF-treated

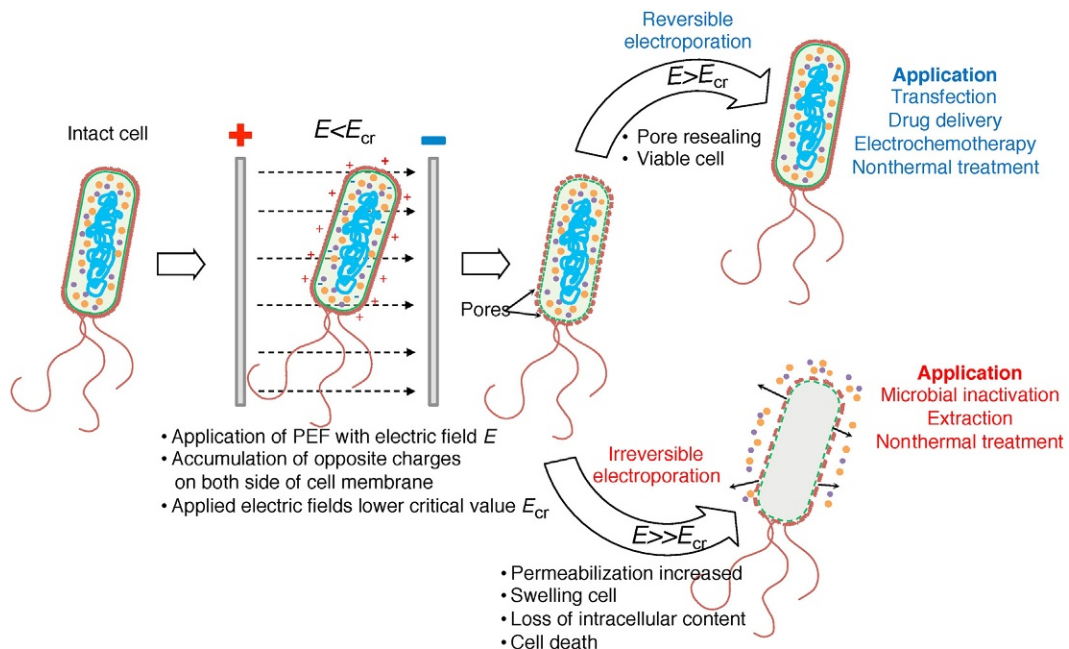


Fig. 2 Schematic representation of reversible and irreversible electroporation (case of *Escherichia coli*) induced by PEF treatment.

microbial cells can positively affect traditional pasteurization technologies.

The energy delivered to the product could be defined in terms of voltage and current transients. For each PEF pulse, the specific energy consumption could be calculated as represented in Eq. (6), and the total specific energy consumption could be calculated as the sum over all pulses as given in Eq. (7).

$$W_k = \frac{1}{m} \int_0^{t_i + \Delta t} u(t) \cdot I(t) dt \quad (6)$$

$$W = \sum_{k=1}^n W_k \quad (7)$$

where n is the number of pulses, m is the product mass (kg), u is the voltage (V), I is the current strength (A), and t_i is the time of one pulse (s).

Ohmic Heating

Ohmic heating (OH) has gained wide popularity as an emerging thermal treatment. When the food matrix contains sufficient amount of water and electrolytes to allow the passage of electric current (usually alternating), OH causes a rapid and uniform heating of the sample, which leads to consistent and rapid heat generation (Saxena et al., 2016). The heating occurs in the form of internal energy transformation (from electric to thermal) within the material (Sastry & Barach, 2000). Therefore, OH can be seen as an internal thermal energy generation technology, and not only as a thermal energy transfer, meaning that it does not depend on heat transfer through a solid/liquid interface (Knirsch et al., 2010). The rate of heat generation in OH is a function of electric field strength applied across the food material (Ramaswamy et al., 2014). Due to the short processing times, OH causes minimum discoloration and maintains the nutritive value of the food (Wang & Sastry, 2002). It has some advantages over conventional heating methods:

- (1) as the technology consists of a volumetric heating, the temperature increase is more uniform than conventional heating methods,
- (2) it does not need convective and conductive heat transfer mechanisms in the heating chamber,
- (3) it reduces the thermal damage and the nutritional losses,
- (4) it increases the overall lethality in the mixture, and

- (5) it provides faster heating than conventional methods (Evrendilek et al., 2012). These features make OH one of the most desirable treatments for liquid food that contains sensitive flavor components that are easily destroyed at longer treatment times. OH presents a large number of current and potential future applications, including its use in blanching, evaporation, dehydration, fermentation, pasteurization, and sterilization (Sasthy et al., 2009).

High-Voltage Electrical Discharges

HVED could be used for numerous applications, including microbial inactivation in liquid foods or chemical removal of organic impurities from water (Puértolas & Barba, 2016). This emerging technology is based on a physicochemical process that occurs when electrical discharges are in contact with liquid media (Barba et al., 2015; Boussetta et al., 2013). This process of dielectric breakdown is the result of ionization of the liquid upon applying a high voltage (30–40 kV) and intensity (~ 10 kA) pulse of short duration (μ s-ms) between two electrodes. The mechanism of action of HVED could be summarized in three phases: (i) electric pulse generation, (ii) current discharge (prebreakdown phase power), and (iii) electric arc formation (electrical breakdown) (Boussetta & Vorobiev, 2014).

The bubbles that are initially present in the water or formed due to localized heating can accelerate the process. If the potential difference between the electrodes is high enough, the electron avalanche occurs, and constitutes the starting point to spread the current from the high-voltage electrode (needle electrode) to the ground one (usually plane geometry). Besides electrical damage produced during this process, several associated phenomena (pressure waves of high amplitude, cavitation, turbulence in the liquid, production of reactive species, etc.) can occur, with the consequent energy release, thus facilitating the fragmentation of cell tissues or microbial inactivation (Boussetta & Vorobiev, 2014). Some of the main benefits of HVED compared to conventional treatments are:

- (i) higher mass transfer,
- (ii) lower processing time,
- (iii) lower processing temperature,
- (iv) minimal degradation of thermosensitive compounds (antioxidants, flavors, proteins, etc.), and
- (v) reduction in the energy cost and environmental impact.

Generally, equipment for the electric power treatment is constituted of a pulse electric generator (for PEF and HVED) or

AC sinusoidal generator (for OH) and a treatment chamber. The treatment chamber consists of one high-voltage electrode (connected to the generator) and a ground one. The treated suspensions or plant tissues are located between the electrodes, and then the electric field is generated due to the difference of potential. The applied electric field not only depends on the electrical pulse characteristics, but also on the morphology and arrangement of the electrodes and the conductivity of the product (Heinz et al., 2001).

3.1.2 Energy Saving for Pasteurization and Sterilization

Food safety is a crucial issue in the food industry and in microbial inactivation, and it is an essential step in many food processing industries. Thermal processing is an important method for the preservation of canned fruits and vegetables. For food products, the conventional thermal or chemical sterilization methods are limited since many products are sensitive to heat, moisture, and a variety of chemicals. Moreover, traditional decontamination processes are very energy-intensive. For example, for manufacturing canned orange juice, the average energy intensity was found to be 1.12 MJ/kg. The most energy-intensive unit operation was pasteurization at 0.932 MJ/kg, followed by packaging at 0.119 MJ/kg (Wang, 2009). Moreover, the high temperature used during pasteurization may affect the overall quality of final products. In this line, nonthermal electropasteurization could be a good alternative to the thermal processes of pasteurization and sterilization.

Pulsed Electric Fields

Inactivation of microorganisms during PEF treatment (cold pasteurization) can be conducted to minimize the losses of flavors and food quality thereby leading to better organoleptic and functional properties in the treated foods. In addition, the low temperatures used in the PEF process allow the treatment to be energy efficient, resulting in lower environmental impact (Amiali & Ngadi, 2012). Depending on the PEF generator characteristics, the energy cost of a PEF treatment is about 0.12 €/kW/h (Toepfl et al., 2006a). When comparing PEF and high-pressure treatment, the estimated total costs for liquid processing reaches 200–700 €/ton for high-pressure treatment but only 10–80 €/ton for PEF.

Nowadays, more than 300 studies have been published about the impact of PEF on microbial inactivation in different liquid foods (Amiali & Ngadi, 2012; Barba et al., 2015; Buckow et al., 2013; Donsì et al., 2011; Martín-Belloso et al., 2012; Saldaña et al., 2014; Sampredo & Rodrigo, 2015; Yang et al., 2016). However,

this chapter will give only few examples of PEF inactivation to show its energy efficiency. It was reported that after PEF treatment at 70 kV/cm and 80 pulses of 2 μ s each, the inactivation level of 9-log reduction of *Escherichia coli* was achieved (Zhang et al., 1994). The energy required to achieve this inactivation was reported to be only 97 kJ/L. Some authors showed that PEF treatment could be less energy intensive than thermal processing, such as high-temperature short-time processing. For the convectional heat treatment the energy required to heat 49.5 mL of water for $\Delta T=50^{\circ}\text{C}$ was 12 kJ, while the energy needed by PEF was only 10.7 kJ (Ho et al., 1995).

In another study, it was shown that PEF treatment at 20 kV/cm and for 4 ms was able to inactivate all yeasts and bacteria present in wines (Delsart et al., 2016). Moreover, it was demonstrated that the application of PEF had no negative impact on the quality characteristics of wines (i.e., phenolic composition, chromatic characteristics, and physicochemical parameters). Also, this microbial inactivation was performed at low-energy consumption (≈ 320 kJ/L) and in practically isothermal mode ($\Delta T < 10^{\circ}\text{C}$). Another study confirmed the possibility of different bacteria and yeasts (*E. coli* O157:H7, *Lactobacillus delbrueckii* ssp. *bulgaricus*, *Candida lipolytica*, *Saccharomyces cerevisiae*, and *Hansenula anomala*) inactivation in red wine using PEF treatment (Abca & Akdemir Evrendilek, 2015).

Egg products contain a high microbial population (i.e., *Salmonella*) if they were not produced aseptically. The conventional high-temperature short-time (HTST) pasteurization damages the structural and functional properties of egg products while PEF treatment is much safer regarding the retention of original quality of egg products (Yogesh, 2016). Less change was observed in the lipoprotein matrix for PEF-treated liquid whole egg as compared to HTST pasteurization (Marco-Molés et al., 2011). The authors also showed that ≈ 8 -log cycle reduction in *Salmonella enteritidis* count in liquid egg samples was achieved after PEF treatment at 25 kV/cm, corresponding to 200 kJ/kg as energy consumption. In another research study, PEF treatment was used for the inactivation of *Salmonella Typhimurium* and *Staphylococcus aureus* at 45 kV/cm for 30 μ s (419 kJ/kg) and 40 kV/cm for 15 μ s (166 kJ/kg) and around 4- and 3-log cycles reduction of these microorganisms were observed, respectively (Monfort et al., 2010).

The impact of combining PEF and microfiltration (MF) on microbial inactivation in milk was investigated (Walkling-Ribeiro et al., 2011). It was shown that indigenous microorganisms were inactivated by PEF processing of 42 kV/cm for up to 2.1 ms, and energy densities between 407 and 815 kJ/L.

Combination of processing (PEF+MF) resulted in reductions of 5.7-log cycle at 668 kJ/L and even higher inactivation of 7.1-log cycle at 815 kJ/L. It was concluded that combination of PEF and MF could be a potential alternative to the conventional thermal pasteurization of milk. In the same line, *Listeria innocua* was inactivated in whole milk by PEF and thermal treatment (Guerrero-Beltrán et al., 2010). Results demonstrated a 4.3-log cycles inactivation rate of *L. innocua* in the milk treated by PEF at 40 kV/cm for 6 μ s and at a temperature close to 55°C. An energy consumption of 244 J/mL was observed and reported that it could be further decreased to 44 J/mL by a thermal regeneration system.

Likewise, the effect of temperature on PEF inactivation of *E. coli* in apple juice was studied at temperatures ranging from 35°C to 70°C (Heinz et al., 2003). The enthalpy diagram of suggested PEF treatment of apple juice using heat recovery is shown in Fig. 3. Energy requirements (which correlates with processing time) to achieve a 6-log inactivation of *E. coli* during PEF processing of apple juice at 24 kV/cm decreased from 100 to 40 kJ/kg, when the process temperature was increased from 40°C to 55°C, which clearly indicated the enhanced efficiency of PEF at elevated temperatures. During PEF inactivation at energy input of 40 kJ/kg, a temperature increase of 11°C in orange juice occurred. When the pulse width was increased from 0.05 to 1 μ s during PEF treatment at 50 kV/cm, the energy required for PEF destruction of *Salmonella enteritidis* decreased from 44 to 32 kJ/kg (Korolczuk et al., 2006).

These examples of PEF applications as a novel pasteurization process prove its application to improve the energy efficiency. The electro-inactivation could be used in nonthermal mode alone or in combination with other techniques (microfiltration or thermal treatment at mild temperatures). The first commercial application of PEF for the preservation of fruit juices was launched in 2006 in the United States. Since then, different industrial-scale processing machines for liquid and solid products were developed. In Europe, an industrial juice preservation line was installed in 2009 using 20 kV/cm pulses at 40–50°C to extend the chill-stability of fruit juices, including citrus juices and smoothies, from 6 to 21 days. The related PEF processing cost is in the range of US \$0.02–0.03 per liter and is justified due to access to new markets and reduced return of spoiled products (Buckow et al., 2013).

Ohmic Heating

There are only few works published about the effect of OH on microbial inactivation. It was demonstrated that the thermal treatment required for microbial inactivation in food could be

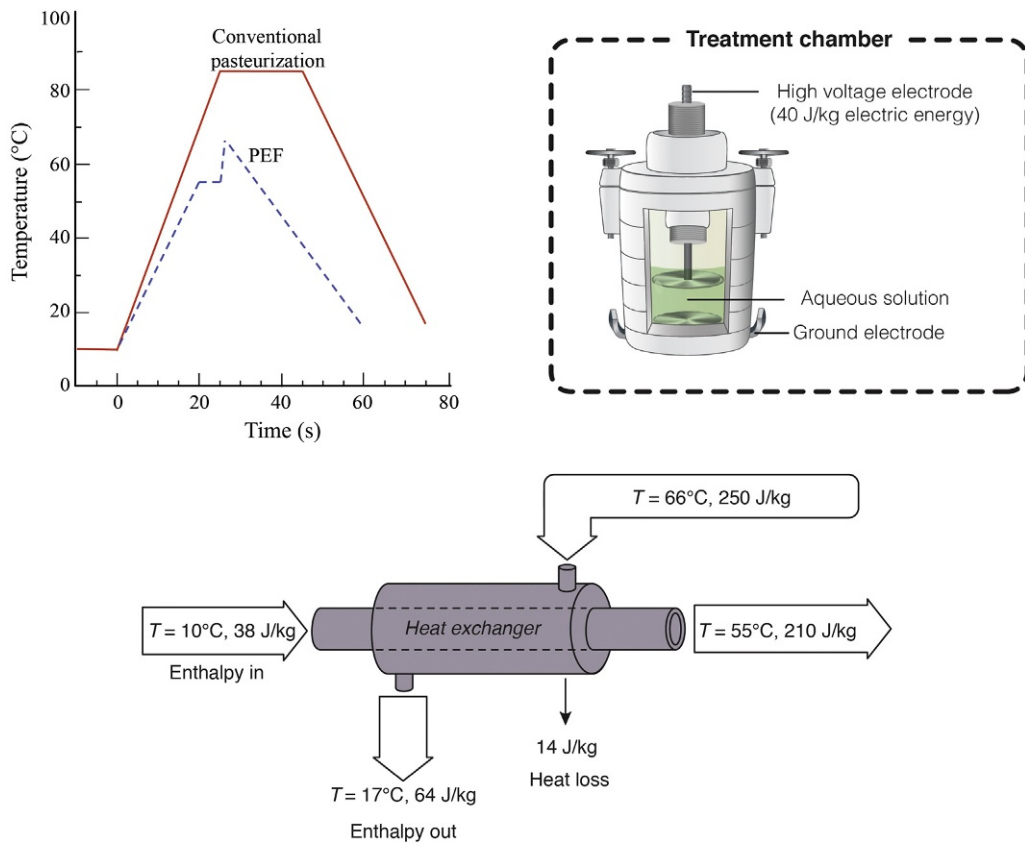


Fig. 3 Temperature-time-profile and enthalpy diagram of a suggested PEF treatment of apple juice with an initial treatment temperature of 55°C, a field strength of 40 kV/cm and a specific energy input of 40 kJ/kg compared to a conventional pasteurization at 85°C and for 15 s. The heat loss in the heat exchanger was estimated for 5%. The profile temperature vs time was reproduced with permission from Heinz, V., Toepfl, S., Knorr, D., 2003. Impact of temperature on lethality and energy efficiency of apple juice pasteurization by pulsed electric fields treatment. *Innov. Food Sci. Emerg. Technol.* 4, 167–175.

potentially reduced in the presence of any sublethal injury or additional lethal effect due to electric current (Palaniappan & Sastry, 2002). The principal mechanisms of microbial inactivation by OH are thermal in nature. Recent research indicates that OH may cause mild nonthermal cellular damage due to the presence of the electric field (Cho et al., 1999; Sun et al., 2008). The principal reason for the additional effect of OH treatment could be its low frequency (usually 50–60 Hz), which allows cell walls to build up charges and form pores (Knirsch et al., 2010). As a main consequence of this effect, the value of decimal reduction time observed for the microbial inactivation under OH is reduced when compared to traditional heating methods. This reduction has

been observed for different types of microorganisms including *Bacillus licheniformis*, *E. coli*, *Bacillus subtilis*, *Streptococcus thermophiles*, and *Byssochlamys fulva* (Cho et al., 1999; Pereira et al., 2007; Sun et al., 2008). Conventional heating was compared to OH to inactivate *Bacillus subtilis* and *Bacillus atrophaeus* bacteria (Cho et al., 1999). It was demonstrated the possibility of OH to decrease thermal inactivation time compared to traditional heating. The inactivation of *S. thermophilus* in milk by OH was conducted by Sun et al. (2008). According to their observations, OH causes higher microbial death than the conventional heating process. It was also demonstrated that complete inactivation of bacteria, yeasts, and molds, as well as reduced pectin esterase activity by 98% could be achieved during ohmic treatments (Leizerson & Shimoni, 2005). During OH treatment, energy cost could be reduced due to reduction of microbial inactivation time as well as decreasing of process temperatures. Moreover, it was shown that OH provided 82%–97% of energy saving along with reducing the heating times by 90%–95% compared to conventional heating (De Halleux et al., 2005).

High-Voltage Electrical Discharges

The effect of high-voltage electrical discharges on microbial inactivation is not sufficiently clear as only few studies were conducted on this subject. However, one hypothesis suggested a number of processes and the presence of some products that are involved in the microbial inactivation during HVED treatment (Anpilov et al., 2002). These factors include the production of ozone, hydrogen peroxide, hydroxyl and superoxide free radicals, UV radiation generated by the discharge itself, as well as acoustic and shock waves.

The energy required to achieve 1-log reduction of *E. coli* by HVED in tap water is in the order of 0.3 J/cm^3 (or $\approx 10^{-4} \text{ kWh/L}$) (Anpilov et al., 2002). Moreover, another microbial strain *Coliphages* required an energy input of 0.15 J/cm^3 for the same result. They also analyzed color, turbidity, pH, ammonium, Fe, Pb, Cr, fluoride, chlorite, nitrate, and sulfate in HVED-treated water. It was concluded that the quality of the treated water fulfilled the necessary standards in the European Union (Council Directives on the quality of water intended for human consumption 80/778/EEC and the new drinking water Directive 98/83/EC adopted by the Council on 3 November 1998).

In another study, the inactivation of *Oenococcus oeni* CRBO 9304, *O. oeni* CRBO 0608, *Pediococcus parvulus* CRBO 2.6 and *Brettanomyces bruxellensis* CB28 was conducted by application of

HVED treatment at 40 kV. It was shown that, for electric treatment at $W=320$ kJ/L and for 4 ms after the HVED treatment, the wine still contained 1-log cycle of *O. oeni* CRBO 9304 and *Brettanomyces bruxellensis*. Likewise, when injected energy was more than 12 J/mL, the maximum inactivation of 2-log reduction was achieved in yellow wine (Yi et al., 2007). Despite the energy efficiency of HVED treatment, its industrialization requires further researches.

3.1.3 Energy Saving for Evaporation and Dehydration

Another highly energy-intensive food preservation process is drying. This unit operation requires up to 20% of total industrial energy use in most developed countries (Kemp, 2012). The main reason for this is the high latent heat of water or solvent evaporation. Latent heat of water evaporation at ambient temperature (20°C) is about 2400 kJ/kg. Thus, the energy required for a drying process is generally in the range of 2.5–2.7 MJ/kg. Note, that an additional sensible heat will be needed if the fruits or vegetables enter to the dryer at ambient temperature, and emerges at a higher temperature (as a vapor). Therefore, the total energy input into a conventional dryer is in the range of 4–6 MJ/kg of removed water depending on the thermal efficiency of the drying systems (Wang, 2009). Moreover, the specific energy consumption by an air-drying system varies significantly with the operating parameters (temperature, air velocity, relative humidity, etc.). For instance, it was demonstrated that the energy requirement was 6.47 and 25.25 kWh/kg for drying of chestnuts at 50°C and 0.5 m/s, and at 40°C and 1.0 m/s in a parallel air flow dryer, respectively (Koyuncu et al., 2004).

The second critical point in drying is the mass transfer through the cells and tissue of solid food. Due to their barrier function of intact cell membranes in the raw material, the diffusion is limited. Furthermore, the tissue structure and the network of intercellular air spaces also affect the mass transfer during drying. The application of external electric fields (PEF or OH) was found to positively affect any subsequent drying processes of plant materials (Jaeger et al., 2014).

Pulsed Electric Fields

PEF pretreatment affects the mass transfer during drying due to induced local structural changes of the cell membrane, and also the increase in permeability due to the appearance of permanent membrane pores. Facilitated mass transfer during PEF-assisted drying was discussed in several published studies (Mahnič-Kalamiza et al., 2014; Witrowa-Rajchert et al., 2014). For instance,

it was reported that the PEF treatment of red beetroot prior to convectional drying resulted in increased moisture diffusivity by 30% (Shynkaryk et al., 2008). Also, it was concluded that drying temperature of PEF-treated tissues could be decreased by $\sim 20\text{--}25^\circ\text{C}$. Adedeji et al. (2008) found that the drying rate of PEF pretreated okra sample was higher than that of untreated tissues. For PEF pretreated carrots, the drying time was reduced by up to 20% at 60°C (Amami et al., 2008). Other authors also observed higher drying rate of carrot pretreated by PEF (1 kV/cm, 20 pulses) in hot-air dryer at 70°C (Gachovska et al., 2008, 2009). More recent investigation showed relatively low drying time reduction (up to 8.2%) of the PEF-treated carrot samples ($W=8\text{ kJ/kg}$, 5 kV/cm and 10 pulses) in comparison to intact tissue (Wiktor et al., 2015a). The ginseng pretreated with PEF of 2 kV/cm resulted in reducing the drying time by 38% (Lim et al., 2012). Recent studies performed on hot-air drying (70°C , 2 m/s) of PEF pretreated apples (50 pulses of 10 kV/cm) showed a reduction in drying time of up to 12% (Wiktor et al., 2013). It was demonstrated that drying the untreated red pepper at 45°C takes 4.9 h, while after PEF pretreatment, this time was reduced by $\approx 34.7\%$ (Won et al., 2015). The drying rates of whole peas can be increased noticeably by PEF treatment (Baier et al., 2015). Moreover, PEF treatments might improve the mass transfer processes without affecting protein's quality. Lamanauskas et al. (2015) showed that the same dryness could be reached (almost two times faster) using PEF pretreatment of *Actinidia kolomikta*. PEF-treated basil leaf samples (1.5 kV/cm) were dried around 50% faster than the control (Kwao et al., 2016). In another study, optimized PEF pretreatment (1.446 V/cm for 28 μs , and 87 pulse) of crystal radish improved its drying rate by 26% and shortened the drying time by more than 14%, while reducing energy consumption (Liu et al., 2016).

Summarizing all the above-mentioned examples, the studied products have positively responded to electroporation treatment with an increase in mass transfer and thus drying rate. In conventional drying, PEF pretreatment decreased the drying time by up to 50% while not exceeding the drying temperature of 60°C . Moreover, drying time or drying temperature reduction will result in a reduction of energy consumption and increase in production capacity (Wu & Guo, 2011; Wu & Zhang, 2014).

Ohmic Heating

The effect of OH on drying process is insufficiently studied compared to PEF treatment. However, it was demonstrated that OH pretreatment highly increased the drying rate of carrot,

potato, and yam samples (Wang & Sastry, 2000). The same decreasing effect ($\approx 24\%$) was obtained by application of OH at 50 V/cm and 45°C prior to vacuum drying of sweet potatoes (Zhong & Lima, 2003). In another work, the authors showed that at a relatively low air-drying temperature ($T = 30^\circ\text{C}$), the OH treatment at $E = 100 \text{ V/cm}$ and $W = 20 \text{ kJ/kg}$ allows increasing the moisture diffusivity to a level higher than that observed for an intact tissue at drying temperature of 50°C. It means that the OH pretreatment allows decreasing the drying temperature approximately by 20°C (Lebovka et al., 2006). The sawtooth pretreated by OH results in a faster drying rate. Also, it was concluded that the increased drying rate effect is most pronounced for intermediate moisture contents (Lima & Sastry, 1999). Moreover, the combination of pulsed vacuum osmotic dehydration and OH, with a subsequent drying at 60°C resulted in greater mass transfer, lower losses of phenolic components, and reduced drying time ($\approx 50\%$) (Moreno et al., 2016). Another application of OH treatment, which is called vacuum evaporation by OH, has also been described in the literature, too (Wang & Chu, 2003). The application of this technique to concentrate orange juice by water evaporation was reported to be more intensive than that of conventional process.

3.1.4 Energy Saving for Freezing

Freezing is another fairly widespread unit operation in the preservation of food products (James et al., 2015). Its benefits are mainly attributed to the fact that food tissues subjected to sub-zero temperatures retain their initial quality, such as nutritive value, organoleptic properties, texture, color, etc. However, freezing of water inside food products consumes a large amount of energy. When water is cooled in a freezer or refrigerator, above the freezing point, the specific heat of liquid water is 4.18 kJ/kg°C. During the phase transition from liquid to solid at 0°C, a latent heat of 335 kJ/kg must be removed. Below the freezing point, the specific heat of ice is about 2 kJ/kg°C. For example, the energy required to freeze food products to -30°C is in the order of 1.2 MJ/kg (Wang, 2009). Thereby, it is quite important to find new alternatives, which will be able to reduce freezing time, thus obtaining frozen food products with improved organoleptic properties and in more energy effective way.

For example, the positive impact of PEF pretreatment on the freezing process in different food products was demonstrated (Ben Ammar et al., 2010; Jalté et al., 2009; Wiktor et al., 2015b). Jalté et al. (2009) evaluated the effect of PEF pretreatment on

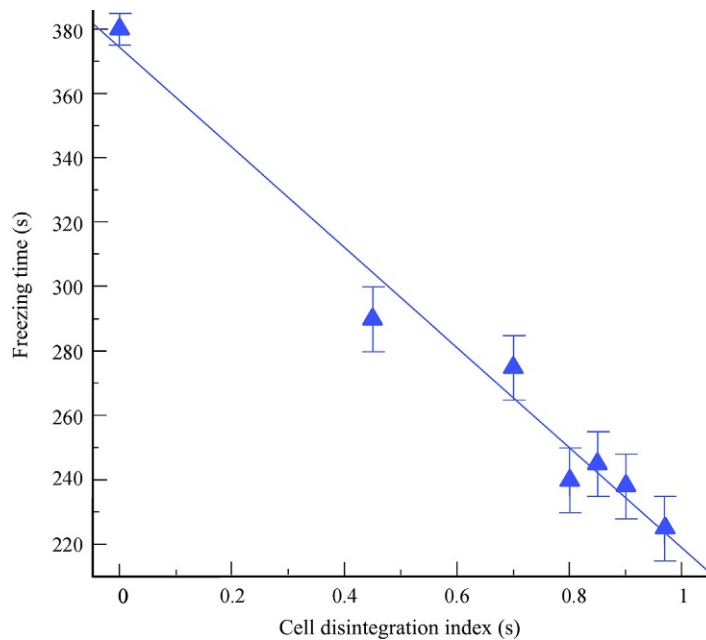


Fig. 4 The effective freezing time vs the cell disintegration index for potato tissues. Reproduced with permission from Jalté, M., Lanoisellé, J.-L., Lebovka, N.I., Vorobiev, E., 2009. Freezing of potato tissue pretreated by pulsed electric fields. *LWT-Food Sci. Technol.* 42, 576–580.

potato freezing and reported that the freezing time of potato tissues could be reduced by 40% due to PEF pretreatment. Moreover, the freezing times for samples pretreated by PEF were significantly reduced as the PEF-induced tissue damage was increased (Fig. 4).

In another research work, the effects of PEF pretreatment on air-blast freezing of potato, green bean, spinach, and onion was evaluated (Ben Ammar et al., 2010). It was demonstrated that the electroporation of plant tissues resulted in freezing time reduction as well as faster ice propagation on freezing. More recent studies have also shown a potential of PEF pretreatment to reduce freezing time of apple (Wiktor et al., 2015b). Indeed, the application of PEF pretreatment was able to reduce total freezing time by 3.5%–17.2% compared to conventional freezing process. For instance, apple tissue pretreated by PEF at 5 kV/cm and 40 kJ/kg exhibited the shortest total time of freezing. Moreover, they found that the phase transition was up to 33% lower in comparison with the untreated samples. Furthermore, PEF pretreatment was able to reduce the precooling time. Reduced

precooling time of PEF-treated apples was explained by the substitution of air by intercellular content that in turn leads to increase the thermal conductivity. In another study, the effect of PEF pretreatment on the state of water in the apple tissues was discussed (Parniakov et al., 2016). It was found that the quantity of freezable water decreased by 11% after PEF treatment. For summarizing, PEF pretreatment showed the possibility to decrease the freezing time by up to 40% and to decrease the quantity of unfreezable water. Both of these aspects showed the possibility of reducing the freezing energy consumption.

3.2 High-Pressure Processing

3.2.1 Principle and Mechanism

High pressure processing (HPP), also called high hydrostatic processing, ultrahigh-pressure processing or isostatic processing, is a nonthermal food processing in which food products are exposed to very high pressure (ranged from 100 to 800 MPa). Basic HPP system consists of pressure vessel, pressurizing system, and supporting units such as heating or cooling components (Fig. 5) (Naik et al., 2013).

Vessel is closed and filled with a pressure-transmitting medium. An automatic deaeration process removed air from the vessel with valve by means of a low-pressure fast fill and drain pump, and high hydrostatic pressure is then generated by

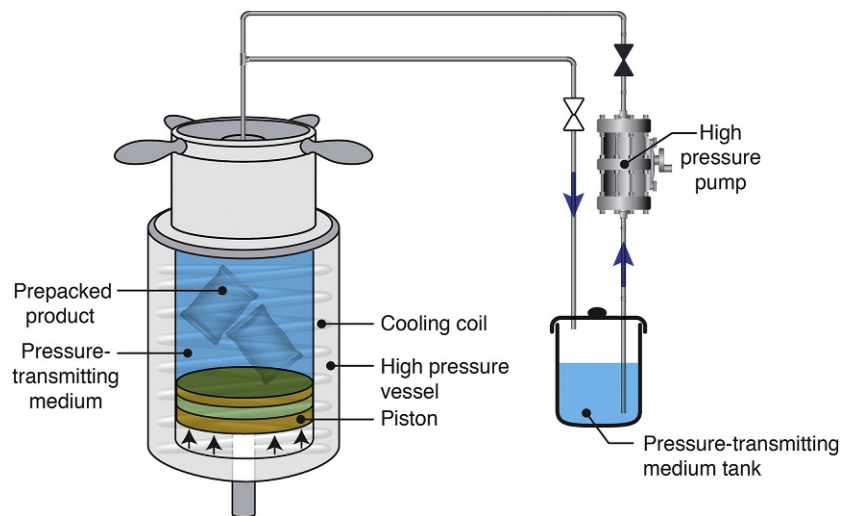


Fig. 5 A typical high-pressure processing system for treating prepacked foods.

direct or indirect compression or by heating the pressure medium (Mertens, 1995). There are some food grade materials to be applied as pressure-transmitting medium including water, castor oil, silicone oil, ethanol, and glycol (Sun, 2014). Although research units are more flexible in terms of using water, oil, or alcohol as pressure-transmitting medium, the majority of commercial scale units are water based (Balasubramanian & Balasubramaniam, 2003). There is no need for additional energy to keep the food sample at determined pressure.

During HPP, a moderate-temperature growth, known as adiabatic heating, could be observed, which has a direct relation with applied pressure. In other words, although temperature at the beginning of the process is around room temperature (25°C), it will increase by pressure increment (about 3.5°C growths per 100 MPa for a water-based unit) during the process (Kingsley, 2013). Therefore, in addition to pressure control, temperature and time also should be monitored. Besides these three crucial factors, the nature of the food product (e.g., low water activity, high fat, and high-protein contents) also plays a vital role in the determination of appropriate pressure to be applied (Hygreeva & Pandey, 2016). It has been reported that, compared to the conventional techniques, using novel processing techniques such as HPP requires lower energy input, fewer resources, and improving the use of raw material or by-products, which are important issues for water and waste management (Toepfl et al., 2006b).

3.2.2 *Energy Saving for Pasteurization and Sterilization*

The application of HPP in biotechnology has been evaluated with interest during the past decade (Xi, 2006). This processing method has been applied successfully for the pasteurization and sterilization of food and pharmaceutical products. For the first time, Hite (1899) reported the effect of HPP on microorganism level reduction of milk using pressure of 650 MPa. The mechanism of action of HPP on microorganism destruction is based on targeting the membrane of biological cells. During pressure exposure, ionization in water, and acid molecules as well as alteration of proteins and lipids increase will be occurred, which subsequently kill microorganisms (Wang, 2008). Generally, for reduction rate of growth and reproduction of microorganisms, a mild level of pressure (10–50 MPa) is enough but for microbial inactivation higher level is needed (Bajovic et al., 2012). It has been proved that Gram-positive bacteria are more pressure resistant than Gram-negative ones, molds and yeasts as a result of structural differences in the cell envelope (Pilavtepe-Celik et al., 2008).

Several studies have been conducted in terms of using HPP for juice pasteurization and some of them have compared HPP with the conventional heat pasteurization process. Bull et al. (2004) evaluated the effects of HPP (600 MPa/20°C/60 s) and thermal pasteurization (65°C for 1 min and 85°C for 25 s) on microbial population of orange juice. They reported that HPP resulted in the lowest microbial population over 12 weeks and consequently the longest shelf life compared to thermal pasteurization. They also confirmed the equality of nutrient content of juices obtained by HPP and thermal one. Similar results were obtained for comparison of HPP (400 MPa/40°C/1 min), PEF (35 kV/cm/750 μ s) and traditional thermal pasteurization (low pasteurization (70°C/30 s), high pasteurization (90°C/1 min)) of orange juice (Sánchez-Moreno et al., 2005). The authors observed better preservation of bioactive components (vitamin C, carotenoids, and flavanones) after HPP and PEF compared to traditional pasteurization. Timmermans et al. (2011) indicated the effectiveness of HPP (600 MPa/5°C/1 min) and PEF (23 kV/cm for 2 μ s/90 Hz), on industrial scale, as two best methods for shelf-life extension of orange juice from 9 to 20 days up to 2 months (at 4°C of storage) compared with mild pasteurization (preheated to 45°C, then heated to 72°C for 20 s). In another investigation, HPP (400 MPa/40°C/1 min) led to notable elevation of the total levels of extracted carotenoids and flavanones (45.19% and 15.46%, respectively) and on vitamin A amount (30.89%) in comparison with the untreated sample, whereas no significant change was observed for low pasteurization (70°C/30 s) (Plaza et al., 2011). Landl et al. (2010) introduced HPP (400 and 600 MPa/5 min/20°C) as a new opportunity for the apple processing industry compared to conventional pasteurization (75°C/10 min) due to more fresh-like, value-added apple products with reasonable shelf life. A comparison study about the effects of HPP (400 MPa/10 min, 500 MPa/5 min, 600 MPa/2.5 min) and HTST (110°C/8.6 s) on microbial activity of purple sweet potato nectar showed better performance of HPP in terms of higher shelf life than HTST (Wang et al., 2012).

Concerning sterilization, HPP alone indicated little impact on spores, but using combination of HPP with other methods (e.g., heating) can sterilize food products. Reddy et al. (2006) demonstrated that the application of HPP (827 MPa), with 95°C heating for 10 min, resulted in reduction of *Clostridium botulinum* spores (17-B) in phosphate buffer by 5.5-log, however its $D_{95^\circ\text{C}}$ was determined to be 22 min. Daryaei and Balasubramaniam (2013) reported 2.3 times lower $D_{100^\circ\text{C}}$ -value of *Bacillus coagulans* spores (158 A) by treatment of tomato juice with HPP (600 MPa/105°C/

0.19 min or 600 MPa/75°C/2.1 min) than that of thermal inactivation (100°C), which was 1.66 min. A 3-log reduction in *Bacillus amyloliquefaciens* spores was observed by application of combined HPP and heat (600 MPa/105°C/5 min), while the corresponding heating resulted in just <1-log reduction (Devatkal et al., 2015). Silva et al. (2012) demonstrated that the inactivation of *Alicyclobacillus acidoterrestris* spores in orange juice at low temperature is feasible by using HPP (600 MPa and 45°C or 400 MPa and 65°C) while higher temperature (85–95°C) is needed when thermal processing was applied. It was reported by Pereira and Vicente (2010) that HPP application led to reduction of required input energy for sterilization of cans from 300 to 270 kJ/kg compared to conventional sterilization. Toepfl et al. (2006b) indicated a compression energy recovery rate of 50% by utilization of a two-vessel system or pressure storage. This energy recovery implies a particular energy input of 242 kJ/kg, which will be needed for sterilization and corresponds to a decrement of 20% in the total energy requirements.

3.2.3 Energy Saving for Extraction of Active Ingredients

Application of HPP for improving the extraction of active ingredients from natural biomaterials has received increased interest during the last decade. The applied pressures in the HPP treatment of biomaterials have little impact on covalent bonds and application of this method can change the structures of fragile foods through cell deformation, cell membrane damage, or protein denaturation (Bennett et al., 1997). Based on the mass transfer theory, the permeability of cells treated under pressure is enhanced (Yan, 2002). According to the phase behavior theory, the solubility will also be enhanced by increasing the pressure (Le Noble, 1988; Sadus, 1992). The differential pressure between inside and outside the cell membrane treated under HPP is so large that it will cause instant permeation. This causes the concentration between the cell membranes inside and outside to reach equilibrium in a short time.

Previous studies showed that using the HPP method in extraction of active ingredients could reduce processing time and power consumption, increase extraction yields, provide extractions contain fewer impurities, and have no negative impact on the activity and structure of bioactive compounds (Jun, 2013). Moreover, this extraction method could be performed at ambient temperature without any heating process, except for the temperature increase due to the compression (Corrales et al., 2009; Sánchez-Moreno et al., 2004).

Generally, the most important HPP extraction parameters affecting the recoveries are type of solvent and volume, pressure intensity, temperature and time of extraction, and the number of cycles (Jun et al., 2010). These parameters need to be optimized to obtain the highest recovery.

Wang et al. (2012) evaluated the application of HPP for the extraction of polysaccharide from *Lentinus edodes* stems (LES) at room temperature. The maximum yield of polysaccharide (53.62 mg/g) was obtained at a pressure of 210 MPa, the solvent-to-solid ratio at 26 mL/g and the holding time at 20 min. Application of HPP showed dominant advantages including higher yield and shorter extraction time compared to the conventional extraction method. Recently, Du et al. (2013) studied the feasibility of using HPP to extract astaxanthin from shrimp wastes at room temperature. The maximum yield of astaxanthin (89.12 μ g/g) was observed at a pressure of 210 MPa, a liquid-to-solid ratio of 32 mL/g, and a pressure holding time of 10 min. Compared to the conventional methods, application of HPP resulted in higher yield at shorter extraction time. Shouqin et al. (2007) also investigated the extraction of ginsenosides using ultrahigh-pressure extraction and showed the advantages of using this method (e.g., higher extraction yield, less extraction time, lower energy consumption, and less impurity in extraction liquid) compared to the conventional extraction techniques. Xi (2006) evaluated the effect of HPP on the extraction of lycopene in tomato paste waste. When compared to solvent extraction, the application of HPP treatment increased the extraction yield and reduced the required processing time. Moreover, the molecular structure of lycopene was not destroyed using this method.

In another study, the application of HPP for the extraction of caffeine from green tea leaves was investigated (Jun, 2009). The highest yields ($4.0\% \pm 0.22\%$) were observed at ethanol concentration of 50% (mL/mL), liquid/solid ratio of 20:1 (mL/g) and pressure of 500 MPa for 1 min. They concluded that the application of HPP for the extraction of caffeine from green tea leaves has several advantages including shorter extraction time, higher extraction yield, and lower energy consumption. In addition to consumer benefit and reducing the energy costs, a key benefit of HPP treatment is its applicability to packaged foods, which prevents the recontamination of products. However, although the potential of using HPP treatment for improving the energy efficient has been clearly described, the high investment costs and cost-intensive maintenance has made the industrial applications of this technique difficult.

3.3 Microwaves

Microwaves are a form of electromagnetic energy with frequencies in the range of 0.3–300 GHz (Koubaa et al., 2015). This system has been first applied for analytical studies in the late 1970s. The energy produced by microwaves is normally higher than other thermal treatments because of generating efficient volumetric heating (Chemat & Cravotto, 2013; Koubaa et al., 2016b). Several studies have described the applications of MW heating in food processing such as drying (Feng et al., 2012; Wray & Ramaswamy, 2015), pasteurization and sterilization (Barbosa-Cánovas et al., 2014; Hong et al., 2016), thawing (Sakai, 2010), tempering (Curet et al., 2013), baking (Therdthai et al., 2016), and extraction (Kate et al., 2016).

Microwave-assisted extraction techniques have been extensively applied for the extraction of high-value added compounds and oils from plant sources (Koubaa et al., 2015, 2016b; Roselló-Soto et al., 2015). Pretreatment of plant materials (e.g., oilseeds) using MW results in higher extraction yields and increased mass transfer coefficients. Several studies have evaluated the effect of MW pretreatment on the extraction efficiency of high-valued compounds from plant sources and demonstrated the advantages of using this method, in terms of energy saving, over conventional techniques. For instance, recently, coaxial MW-assisted hydrodistillation of essential oils from different plants namely lavender, rosemary, sage, fennel seeds, and clove buds was investigated (González-Rivera et al., 2016). Compared to the conventional methods, application of coaxial MW-assisted hydrodistillation resulted in a higher concentration of oxygenated monoterpenes, which was alongside with better product selectivity, energy savings, and lower heating time. The electric energy required for conventional heating to start the hydrodistillation from ambient to boil temperature was 1.43 kJ/g, while this was reduced to 0.63 kJ/g by the in situ irradiation of MW energy. Tigrine-Kordjani et al. (2006) evaluated the application of MW-accelerated distillation for extraction of edible essential oils from rosemary (*Rosmarinus officinalis* L.). Compared to the hydrodistillation method, extraction of essential oils with MW-accelerated distillation resulted better energy saving, extraction time (30 min vs 3 h), oxygenated fraction (59% vs 46%), product yield (0.6% vs 0.6%), and product quality. Aliboudhar et al. (2015) investigated the extraction of essential oils from leaves and stems of *Anacyclus clavatus* using MW-assisted hydrodistillation method and reported better energy savings, extraction time, and product quality than classic hydrodistillation technique. Djouahri et al. (2013)

evaluated the effect of MW-assisted hydrodistillation technique on chemical composition, antioxidant, and antiinflammatory activities of the essential oils extracted from *Tetraclinis articulata* (Vahl) Masters. Compared to the conventional hydrodistillation method, MW-assisted hydrodistillation technique was found to be more advantageous and showed better energy savings and extraction time (90 min vs 180 min) as well as extraction yield (0.54% vs 0.56%).

In another study, Boukroufa et al. (2015) optimized the extraction of essential oils, polyphenols, and pectin from orange peel using MW (without adding any solvent) and compared to steam distillation extraction method. Application of MW power of 500 W for 3 min resulted in maximal pectin extraction yield (24.2%), which was higher than conventional extraction (18.32%) in 120 min. Combination of MW, ultrasound and the recycled in situ water of orange peels provided extracts with higher value-added compounds in shorter time and showed a better energy saving, cleanliness, and reduced waste water. Quoc et al. (2015) investigated the extraction of pectin from pomelo (*Citrus maxima*) peels with MW and tartaric acid assistance. The highest pectin extraction yield (23.83%) was obtained at pH of 1.5, rate of material to solvent ratio of 1:40, irradiation time of 9 min, and irradiation power of 660 W. Application of tartaric acid solvent and MW improved the pectin extraction quality and yield and caused better time and energy saving.

Lakshmi et al. (2007) determined the amount of energy consumption under normal and controlled techniques of cooking, with unsoaked and presoaked rice, in a MW oven at different power levels. In terms of energy consumption, MW cooking was reported to compete with domestic cooking methods (e.g., pressure cooking in a LPG stove). Compared to other cooking methods, MW cooking revealed the advantage of shorter cooking time. In another study, the application of MW showed great advantages over conventional techniques including shorter extraction time, energy saving, and selectivity for the recovery and evaluation of carvone and limonene from flaked dill fruits (*Anethum graveolens* L.) (Chemat & Esvelde, 2013).

Up to now, many machines have been constructed for producing dried-foods with better quality and lower energy consumption (Zhang et al., 2015). Fig. 6 shows a schematic representation of continuous microwave drying system. The temperature distribution during MW-drying has been reported to be more uniform compared to the conventional drying techniques (Jiang et al., 2012).

Several studies reported the application of MW alone or in combination with other methods in drying of different food

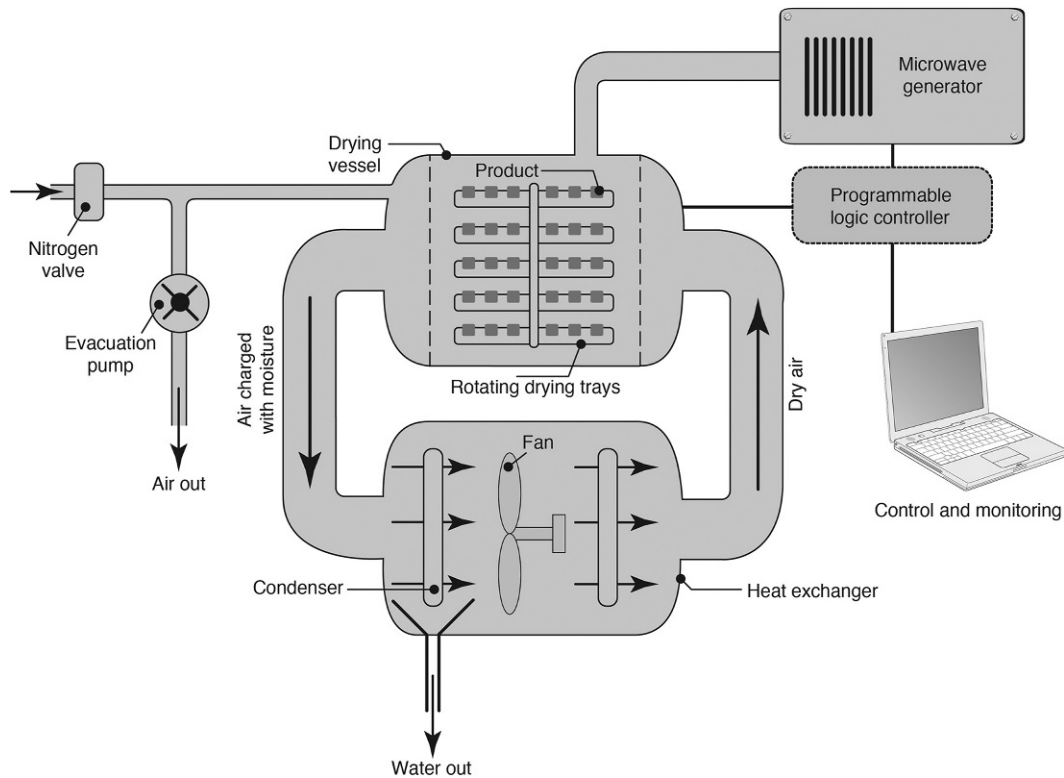


Fig. 6 Schematic representation of continuous microwave drying system.

products. For instance, the feasibility of MW technology for drying and roasting of peanuts was investigated (Megahed, 2001). The authors reported that although using MW roasting resulted in formation of undesirable lipid oxidation products, application of this method for blanching could be considered as an alternative to traditional blanching techniques due to the higher operation speed, better energy savings, and process control efficiency.

It has been reported that the application of MW drying alone has some disadvantages including nonuniform heating, probable textural damage, and MW limited penetration depth into the food products (Zhang et al., 2006). Alternatively, application of parallel drying methods, which involves the simultaneous use of two or more drying techniques in one machine, leads to higher drying efficiency than using a drying system alone. For example, Varith et al. (2007) evaluated the effect of combined microwave hot air on peeled longan drying. The maximum drying efficiency was obtained using a step-wised drying process at 40°C hot air with

MW power of 450 W for 1.7 h, followed by 60°C hot air with MW power of 300 W for 3.3 h. Application of combined microwave-hot-air method resulted in decreasing the drying time (64.3%) and specific energy consumption (48.2%), compared to the samples dried with hot air alone at 65°C. [Feng and Tang \(1998\)](#) reported that the combination of MW heating with spouted bed could reduce the drying time of diced apples by more than 80%. Several studies reported the effect of MW-assisted spouted bed drying on potato cubes ([Yan et al., 2010b](#)), carrot pieces ([Yan et al., 2010a](#)), and diced sweet potato ([Yan et al., 2013](#)). Compared to the microwave freeze drying, application of this method was suggested as a good alternative for making high-quality snack foods with lower energy consumption.

3.4 Ultrasounds

3.4.1 Principle and Mechanism

Ultrasound (USN) technology is nowadays implemented in numerous food processes, due to its several advantages over conventional processing ([Koubaa et al., 2016b](#)). It offers reducing significantly the processing time (seconds to minutes), with high accuracy, along with a consumption of reduced energy, compared to conventional heating ([Chemat et al., 2011](#)). The amount of energy saved during food processing by USN depends on the goal to be reached (e.g., extraction of bioactive compounds, sterilization, etc.). Therefore, USN was implemented in numerous processes such as extraction of bioactive compounds ([Koubaa et al., 2016a](#)), freezing ([Li & Sun, 2002](#)), sterilization ([Chandrapala et al., 2012](#)), cutting ([Zahn et al., 2006](#)), drying ([de la Fuente-Blanco et al., 2006](#)), bleaching ([Su et al., 2013](#)), and many other applications.

The main phenomenon described in the literature for the mechanism of action of USN is cavitation. A sonotrode generates an intense sound wave (20 kHz–1 MHz), which passes through a liquid, and creates compression and rarefaction regions. During rarefaction, if the energy is high enough, a cavity or bubble could be formed. After a certain number of compressions and rarefactions, the bubble reaches an instable size and may collapse violently. High local pressure and temperature are accompanied with implosion, which could reach 50 MPa and 5000°C, respectively ([Barba et al., 2016](#)). The energy input during USN treatment corresponds to the product of power output (kW) and the time of exposure, which is directly related to the flow rate through the ultrasonic device (L/h) ([Patist & Bates, 2008](#)). [Fig. 7](#) represents a

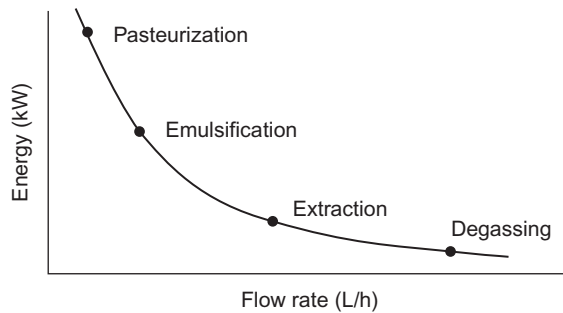


Fig. 7 Generalized relationship of flow rate (L/h) vs energy (kW) for some ultrasonic applications. Reproduced with permission from Patist, A., Bates, D., 2008. Ultrasonic innovations in the food industry: from the laboratory to commercial production. *Innov. Food Sci. Emerg. Technol.*, Food Innovation: Emerging Science, Technologies and Applications (FIESTA) Conference 9, 147–154.

very general relationship between energy and flow rate for some ultrasonic applications. Regarding the numerous applications of USN in food industry, this chapter is mainly focused in analyzing the energy saving using USN for pasteurization and sterilization, evaporation and dehydration, and chilling and freezing.

3.4.2 Energy Saving for Pasteurization and Sterilization

During USN treatment, when a vapor bubble implodes in close proximity to a wall (e.g., cell membrane), fluid cannot flow in from all directions, and a microjet of fluid is formed in the direction of the wall, with a velocity reaching up to 100 m/s. When microjet reaches the cell surface, it creates a microfracture leading to cell death. Other phenomena were also described in the literature, in addition to local high pressure and temperature, and including the production of free radicals that cause the DNA damage, and microstreaming causing thinning of cell membranes (Torley & Bhandari, 2007).

Treating a liquid food containing microorganisms by USN allows generally its pasteurization. Using USN as an antimicrobial agent, alone or combined with other methods, dates back to many years ago (Earnshaw, 1998; Earnshaw et al., 1995; Mañas et al., 2000; Piyasena et al., 2003; Raso & Barbosa-Cánovas, 2003; Ross et al., 2003). Although efficient with different sensitivities, USN treatment allows the destruction of wide varieties of microorganisms, including bacteria (Cruz-Cansino Ndel et al., 2016; Piyasena et al., 2003; Ross et al., 2003), bacterial spores (Evelyn & Silva, 2015; Sagong et al., 2013), yeasts (Gao et al., 2014), fungi (Entezari et al., 2004; Idrissi et al., 1996; Scherba et al., 1991), fungal spores

(López-Malo et al., 2005), protozoa (Oyane et al., 2005), and viruses (Scherba et al., 1991).

Using USN alone or combined with other processes (e.g., moderate heat, high pressure, antimicrobials, and so on) to inactivate microorganisms in liquid foods reduces significantly the processing time and the energy usually required to heat the medium for pasteurization and sterilization. Thermosonication, which consists of combining sonication and moderate heat, demonstrated significantly lower processing time and reduced energy to achieve the same lethality values as with conventional processes (Herceg et al., 2012; Joyce et al., 2003). Many other examples of thermosonication were described in the literature (Ercan & Soysal, 2013). Keeping the temperature generally between 40°C and 50°C during ultrasonic pasteurization, lower than the temperature used in conventional pasteurization, is the advantage of using this method to preserve further the nutritional and sensory properties of the treated products.

3.4.3 Energy Saving for Evaporation and Dehydration

Conventional air drying could be enhanced when it is combined with USN. In fact, USN can increase the drying rate due to medium agitation, resulting in reducing the external barriers and the thickness of the boundary layer. USN enhances also the movement of internal liquid by the succession of compression and rarefaction from the core of the material to the surface (Mulet et al., 2003). Numerous food products were subjected to air drying combined with USN, including slices of carrot (Gallego-Juarez et al., 1999) and onion (Da-Mota & Palau, 1999), potato (Bartolome et al., 1969), rice (Muralidhara & Ensminger, 1986), corn and wheat (Huxsoll & Hall, 1970), and fish products (Nakagawa et al., 1996). It is well known that USN could be performed in liquid or solid media, however, some systems were developed to generate USN in gases, which allows its use in combination with air drying.

Combining air drying with USN has the greatest benefit of reducing considerably the drying temperature and/or the drying time compared to the use of air drying alone. For instance, it was demonstrated that the time required to dry carrot slices was reduced from 35 to 25 min when using air drying alone at 60°C, and air drying combined with USN at the same temperature, respectively (Gallego-Juarez et al., 1999). A similar result was observed during walleye pollack surimi (fish product) drying from 73% moisture to 60%, where combined USN and air drying reduced the time of drying from 260 (0 db) to 70 min (155.5 db),

and from 100 (0 db) to 70 min (155.5 db), at 20°C and 50°C, respectively (Nakagawa et al., 1996).

In the same line, a USN sonotrode was incorporated into spray-drying tower, and demonstrated its effectiveness by reducing the temperature required for drying without USN, as well as the size of the obtained droplets (Cohen & Yang, 1995; García-Pérez et al., 2006). These examples and others demonstrate the promising potential of implementing USN in food industry in combination with air drying for energy saving purposes.

3.4.4 Energy Saving for Freezing

Freezing process could be assisted by ultrasounds leading to both increasing the quality of the food product and reducing the time required for freezing. These aspects were well reviewed in the literature (Cheng et al., 2015; Zheng & Sun, 2006). In fact, USN allows increasing the heat mass transfer coefficient (Lima & Sastry, 1990), as well as the nucleation rate and crystal growth rate during crystallization (Mason, 1998). In fact, USN is able to alter the crystallization process during the freezing process of food products, most probably through cavitation phenomenon, which reduces the size of the formed crystals and leads to reduced alteration during thawing.

One of the major drawbacks of combining USN and freezing is the generation of heat by USN, which may reduce the efficiency of the whole process. Although this energy losses by heat generation, applying USN during freezing reduces the time required by conventional freezing. For instance, applying USN powers of 15.9 and 25.9 W decreased the time required to freeze potato pieces, from 0°C to -7°C (Li & Sun, 2002). In addition to reducing the freezing time, selecting the appropriate power of USN has shown significant impact in the microstructure of frozen potato (Sun & Li, 2003).

More recently, the effect of ultrasound-assisted freezing on the physicochemical properties and volatile compounds of red radish was investigated (Xu et al., 2015). By applying USN, the time required for freezing was reduced by 14% and 90%, compared to slow freezing (SF), immersion freezing (IF), respectively. Moreover, USN-assisted freezing led to retain most of the phytonutrients (anthocyanins, vitamin C, and phenolics), and preserved the microstructure of the tissues, with higher calcium content, compared to SF and IF. In the same line, the effect of USN-assisted freezing was applied to strawberries (Cheng et al., 2014). Results showed that the application of USN during freezing allowed inducing nucleation at lower degree of supercooling, compared to control samples. Many other examples have been cited in the

literature showing the beneficial impact of combining USN and freezing for both saving the energy and preserving the microstructure and the composition of the food product (Islam et al., 2014; Xin et al., 2014).

3.5 Infrared Processing

3.5.1 Principle and Mechanism

Infrared (IR) radiation is a form of energy consists of electromagnetic waves in three different regions: the near-infrared (NIR; 0.78–1.4 μm), middle-infrared (MIR; 1.4–3 μm) and far-infrared (FIR; 3–1000 μm) (Mongpraneet et al., 2004). Heat transfer in this method is significantly faster than conventional techniques (Yang et al., 2010) as there is no need to air for IR energy transmission. Generally, as air and gases can absorb very little IR energy, the IR heating process provides efficient heat transfer without contact between the heat source and the material being heated (Sun, 2014). Although NIR produces higher temperature, FIR is the most usable one in food processing as the majority of food compounds absorb this region (Krishnamurthy et al., 2008). Under IR treatment, the most affected molecules are water and organic compounds containing polar groups ($-\text{NH}$, $-\text{CO}$, $-\text{OH}$, $\text{C}=\text{C}$) including proteins, lipids and carbohydrates, which absorb IR energy and consequently changes in the vibration and rotation of molecules will occur. After returning of the molecules into the normal state, the absorbed energy is transferred into heat (Staack, 2008). Table 1 summarizes the IR absorption bands characteristic of chemical groups relevant to the heating of foods (Pan & Atungulu, 2011).

Table 1 Infrared Absorption Bands Relevant to Food Heating

Chemical Group	Absorption Wavelength (μm)	Relevant Food Component
Hydroxyl group ($\text{O}-\text{H}$)	2.7–3.3	Water, carbohydrates
Aliphatic carbon-hydrogen bond	3.25–3.7	Lipids, carbohydrates, proteins
Carbonyl group ($\text{C}=\text{O}$) (ester)	5.71–5.76	Fats
Carbonyl group ($\text{C}=\text{O}$) (amide)	5.92	Proteins
Nitrogen-hydrogen group ($-\text{NH}-$)	2.83–3.33	Proteins
Carbon-carbon double bond ($\text{C}=\text{C}$)	4.44–4.76	Unsaturated fats

3.5.2 Energy Saving for Pasteurization and Sterilization

IR could be applied to inactivate different kinds of microorganisms (e.g., bacteria, spores, yeast, and mold) in both liquid and solid foods. There are several parameters affecting the efficiency of IR heating including IR power level, temperature and depth of sample, peak wavelength, types of microorganisms, physiological phase of microorganisms (exponential or stationary phase), and types of food materials. It has been proved that using higher power of IR produces more energy, which is absorbed by microorganisms and accelerates microbial inactivation. In this regard, [Hamanaka et al. \(2000\)](#) indicated that increasing irradiating powers from 0.5 to 2.0 kW led to higher surface temperature of wheat stack (45–120°C) obtaining 0.83- and 1.90-log 10 colony-forming units (CFU)/g total bacteria after 60 s treatment, respectively.

Some investigations revealed the efficiency of IR in microorganisms' inactivation due to shorter applied time compared to conventional pasteurization. [Ha et al. \(2012\)](#) evaluated the efficacy of NIR heating against *Salmonella enterica* serovar Typhimurium, *E. coli* O157:H7, and *Listeria monocytogenes* in ready-to-eat (RTE) sliced ham in comparison with conventional heating. Time consumption for 4.1-, 4.19-, and 3.38-log reductions in surface-inoculated *Salmonella typhimurium*, *E. coli* O157:H7, and *L. monocytogenes*, respectively, was significantly lower for NIR (1.8 kW for 50 s) than that of conventional heating (180 s). Another study reported that NIR (1 kW for 156 s) resulted in lowering surface-inoculated *L. monocytogenes* by 3.4-log CFU/g of cooked chicken breast meat, however immersion in hot water (75°C for 5 min) led to reduction by 3.15-log CFU/g ([Huang & Sites, 2012](#)). Obviously, such a long treatment time is not applicable in the industry; moreover, organoleptic properties may also change due to denaturation of meat surfaces.

3.5.3 Energy Saving for Evaporation and Dehydration

Application of IR drying not only is an energy, time, and space saving technique compared to conventional methods but also provides higher quality of dried products, easier control of the process parameters, uniform temperature distribution and cleaner operational environment ([Mongpraneet et al., 2002](#); [Navari & Gevaudan, 1992](#); [Sakai & Hanzawa, 1994](#)). [Shi et al. \(2008\)](#) evaluated the drying potential of IR (with average IR intensity of 4 kW/m²) of fresh and sugar-infused blueberries compared

to convective hot-air drying (60°C). They demonstrated higher drying rate of IR with regard to hot-air drying. The reported times of IR for obtaining the final products were 540, 210, 120, and 90 min at 60°C, 70°C, 80°C, and 90°C, respectively. These times corresponded to savings in drying time of 44%, 78%, 88%, and 91% in comparison with the hot-air drying at 60°C (960 min). Lower drying time was obtained for sugar-infused blueberries which may be associated to lower initial moisture content and also much less moisture required to be eliminated for sugar-infused blueberries compared to fresh samples. Pawar and Thorat (2011) attributed energy efficiency of IR dryers to the absorption characteristics of the material, which determines the economic feasibility of the dryer. Another investigation reported that the sample's (fresh apple slices) intense heating by IR causes a temperature gradient in the sample within the short time, thus lesser energy is consumed during IR drying (Toğrul, 2005). IR energy transfer directly from the heating element to the sample surface without heating surrounding air was suggested as another reason for energy saving of this technology compared to conventional methods. Nowak and Lewicki (2004) found several factors affecting energy efficiency of IR drying including the distance between the heating source and food sample, the velocity of the material sheet, the air flow velocity and temperature (if a continuous IR dryer). Swasdisevi et al. (2009) also showed lower energy consumption of IR drying compared to conventional drying method as a result of direct penetration of IR radiation into the inner layer of the material sample (banana slice).

3.6 Ultraviolet and Pulsed Light Processing

3.6.1 Principle and Mechanism

Ultraviolet (UV) and PL processing are both nonthermal techniques, which are considered as promising alternatives for conventional thermal methods. UV light is divided into three regions including: (i) UV-A (315–400 nm), (ii) UV-B (280–315 nm), and (iii) UV-C (200–280 nm) (Choudhary & Bhandla, 2012). Recent advances have shown the great potential of UV as an alternative to conventional methods for improving the shelf life of liquid food (e.g., fresh juices, soft drinks, and beverages) and fresh fruits and vegetables or for postlethality treatment of RTE products (Koutchma et al., 2009).

PL, also known as pulsed UV light, high-intensity broad-spectrum PL or pulsed white light, is a novel technology for surface decontamination using short-time pulses of an intense broad

spectrum, rich in UV-C light (Gómez-López et al., 2007). PL system consists of constituents including power supply, lamp, and configuration device. High energy is received in the lamp leading to an intense pulse, which typically lasts a few hundred microseconds. Produced light includes wavelength from UV (180–380 nm) to NIR (700 nm) (Shariati et al., 2016). It is approximately the same mechanism of microorganism inactivation for both UV and PL (Abida et al., 2014; Anderson, 2008). Two mechanisms of microbial inactivation have been reported including photochemical effect and photothermal effect. The first mechanism is attributed to the presence of UV light, which acts directly on the DNA cells of the microorganisms. The second one is a result of the temperature increment of food materials, due to the absorption of light pulses and dissipation of the absorbed pulses into heat by the surface (Saikiran et al., 2016). Coexistence of these mechanisms is possible and the fluence and target microorganism determines the relative importance of each one (Abida et al., 2014).

3.6.2 Energy Saving for Pasteurization and Sterilization

In 2000, the FDA approved UV light as an alternative treatment method to thermal pasteurization of fresh juice products. For the first time in 2002, UV-C treatment was reported to disinfect drinking water and the results indicated destruction effects against many human pathogens, viruses, bacteria, yeasts, and protozoa (Masschelein & Rice, 2002). Several factors have been proved to play a crucial role in the UV efficiency in terms of microorganism inactivation including UV fluence, transmittance, and composition of treated food sample. For example, higher fluence resulted in more reduction of microbial population. However, higher fluence may lead to nutritional loss, quality decline, and formation of undesirable compounds (Orlowska et al., 2012).

It was reported by Choi and Nielsen (2005) that UV irradiation provides a more cost-effective method to produce safe apple cider compared to thermal pasteurization. Guerrero-Beltrán and Barbosa-Cánovas (2005) demonstrated a 1.34-log reduction of *Saccharomyces cerevisiae* after 30 min of UV treatment of apple juice (at six flow rates (0.073–0.548 L/min) for selected fluences (75–450 kJ/m²)). Similar results were obtained by the same authors for mango nectar treatment by UV at five flow rates (0.073–0.451 L/min) and five UV light doses (75–450 kJ/m²) led to maximum 3-log reduction in *Saccharomyces cerevisiae* population after 30 min (Guerrero-Beltrán & Barbosa-Cánovas, 2006). In addition, mango nectar shelf life was extended up to 20 days. Spoilage organisms' inactivation of UV in the range of

12–147.6 mJ/cm² was evaluated in orange juice and caused 3-log reduction of aerobic bacteria, yeasts, and molds (Tran & Farid, 2004). Extended shelf life of fresh squeezed orange juice was achieved to increase for 5 days with a limited exposure of UV (73.8 mJ/cm²). *E. coli* O157:H7 was selected as the target of many studies for evaluation of UV efficiency due to its high probability to produce food-borne illnesses. Inactivation of *E. coli* O157:H7 in apple juice by UV light (dose of 300 mJ/cm²) was studied (Ngadi et al., 2003). They reported a 4.5-log reduction in which it increased to 4.8-log when UV dose increased. By increment of UV dose to 390 mJ/cm², the inactivation did not exceed 3.5-log indicating that medium transparency to UV affects the microbial inactivation efficacy. Another investigation about the efficiency of UV for *E. coli* O157:H7 reduction was conducted by Wright et al. (2000) in unpasteurized apple cider at 254 nm with dosage range between 9.4 and 61.0 mJ/cm². They found exponentially destruction of *E. coli* (3.81-log CFU/ml) with UV doses between 4.0 and 6.5 mJ/cm². UV inactivation ability of *E. coli* O157:H7 strains (933, ATCC 43889, ATCC 43895) in apple cider was studied in unfiltered apple cider using UV-C light (λ =254 nm) dose of 14 mJ/cm² (Basaran et al., 2004). The highest inactivation (6.63-log) was found to be *E. coli* O157:H7 ATCC 43889 in comparison with 5.93-log reduction for the other two strains.

It has been proved that the amount of suspended solids and fibers present in a liquid sample significantly affects the required UV dose. For example, apple juice needed lower doses of UV to achieve efficient decrement of microbial load. However, orange juice containing pulp and nectars required higher doses of UV light due to suspended solids' role in microorganism's protection against the action of UV treatment (Turtoi & Borda, 2013).

The population of *E. coli* inoculated in apple juice lowered by 7.29-log CFU/ml after only 3 s of a PL treatment with a fluence amounting to 88,000 mJ/cm² (Sauer & Moraru, 2009). Cold pasteurization of milk was reported to be efficient when treated by PL at a minimum dose of 12.6 J/cm² delivered in 56 s (Smith et al., 2002). Pataro et al. (2011) investigated the lethal effects of PL (100–110 nm/3 Hz/360 μ s) against *L. innocua* (11288) and *E. coli* (DH5- α) inoculated in apple juice (pH of 3.49) and orange juice (pH of 3.78). They found that depending on the type of microorganism and the absorption properties of the liquid food, inactivation effect of PL differs. PL treatment of 4 J/cm² led to the microbial load reductions in apple and orange juices for *E. coli* as 4.00- and 2.90-log, respectively, and for *L. innocua* were 2.98- and 0.93-log, respectively. PL treatment (200–350 nm/5–100 pulses) was chosen to inactivate bacterial suspension contained *E. coli*

and *Salmonella enteritidis* and led to 9-log reduction for both microorganisms with 100 pulses of 9 J (Ghasemi et al., 2003).

It was reported that fungal spores (e.g., *Aspergillus niger* and *Fusarium culmorum*) are more resistance to PL treatment in comparison with bacteria such as *E. coli* and *Bacillus cereus*. This phenomenon could be associated with the presence of protective dark pigments in the wall layers that surround the spore form (Anderson et al., 2000; Oms-Oliu et al., 2008). Wekhof et al. (2001) observed that about 4.8-log of *A. niger* spore inactivation achieved by 5 PL flashes at 1 J/cm². Different resistance also exists among bacteria, as Gram-positive bacteria (e.g., *B. cereus*) were found to be more resistant to the influence of PL than Gram-negative bacteria, such as *Salmonella enteritidis* and *E. coli* (Anderson et al., 2000). This is attributed to the cell wall composition variation and different protective and the repair mechanisms (Oms-Oliu et al., 2008).

Meat products are also considered as a target for PL treatment to inactivate the microorganisms. In 2009, Uesugi & Moraru conducted a research using PL technology (9.4 J/cm²) to reduce *L. innocua* on the surface of Vienna sausages. They observed a 1.39-log CFU reduction after PL treatment and reported no notable growth after 8 days of storage at 4°C. The feasibility of PL in terms of reduction of *L. monocytogenes* and *E. coli* O157:H7 on the muscle and skin side of raw salmon filets was also examined by Ozer and Demirci (2006). PL treatment at a distance of 80 mm with 180 pulses resulted in a reduction of 0.30- and 1.09-log CFU/g in *E. coli* O157:H7 on the muscle and skin side, respectively. Concerning *L. monocytogenes*, reductions of 0.74- and 1.02-log CFU/g were found after 180 pulses at a distance of 80 mm on the salmon muscle and skin, respectively. Anderson et al. (2000) indicated that as the number of pulses increased lethal effect improved. Authors reported the constant numbers of microorganisms as a function of the number of pulses after that the inactivation starts. Generally, according to reported data, microbial level reduction increases with distance decrement from the sample (Hillegas & Demirci, 2003; Ozer & Demirci, 2006), with pulse number increment and with sample depth (thickness) lowering (Elmnasser et al., 2007).

4 Advantages and Limitations of Using Novel Technologies

Novel technologies mentioned in this chapter hold potential for application in different segments of food industry to produce high-quality and safe food products. Improvement of the quality

of the final product is always an important goal for manufacturers and these new methods are concerned as great alternatives to achieve this target. Besides all advantages of these novel techniques such as clear environmental benefits, overall energy efficiency enhancement (Pereira & Vicente, 2010), and better retain of products properties (e.g., color, odor, and nutrient components), they have some limitations that should be taken into account. A summary of both advantages and limitations of these novel techniques is listed below.

Pulsed electric fields: Some of PEF benefits include destruction of vegetative cells with preservation colors, flavors, and nutrients, relatively short treatment time, and no environmental hazard. On the other hand, PEF has some limitations such as no effect on spores (Fryer & Versteeg, 2008) and enzymes, high initial cost (Min et al., 2007) and possible adverse effects due to products of electrolysis (Kumar et al., 2015).

High-voltage electrical discharges: This method, same as other nonthermal techniques, also benefits from more preservation of colors, odors, and nutrients with no temperature increment during treatment by arc discharge as well as inactivation of microorganisms and enzymes (Barbosa-Cánovas, 1999). The most important problem using high-voltage electrical discharges is the possibility of treated sample to be contaminated with chemical products of electrolysis and disintegration of food particles by shock waves (Stoika et al., 2013).

Ohmic heating: The major benefits of OH could be summarized as: faster achievement of temperature required for HTST processes, quicker heating rate with uniform heating of liquid sample, lower overheating problems in comparison with conventional heating, less maintenance costs, negligible heat losses, and no residual heat transfer after the current is shut off (Pereira & Vicente, 2010). Three main disadvantages have been reported for OH application; first one is its high costs of commercial systems. The second drawback is related to the food type with fat globules, which are nonconductive due to the lack of water and salt. Any pathogenic bacteria that could be located in these globules may receive lower heat treatment than the other parts of the sample. The third one is associated with the electrical conductivity of a substance. By increment of the temperature system, higher electrical conductivity is observed as a result of the faster movement of electrons, which may lead to higher possibility of “runaway” heating (Anderson, 2008).

High-pressure processing: HPP can offer several advantages including minimized thermal degradation of food compounds and therefore high retention of flavor, color, nutritional value,

and depression of freezing point of water. This treatment exerts pressure uniformly and instantaneously through the food sample independently of its mass, shape, and composition (Pereira & Vicente, 2010). There is lower need to compress a solid or a liquid to 500 MPa as compared to heating to 100°C (Tewari, 2007). However, there are still limitations for HPP application such as high installation cost, essential need of presence of water in food samples due to being a compression-based process, and higher attention requirement for structurally fragile foods (Naik et al., 2013).

Microwaves: In comparison with conventional methods, microwave technology have the following benefits: (a) due to penetration of microwave into food sample, cooking takes place throughout the whole volume of food internally with a significant reduction in the processing time and energy, (b) preservation of nutrients, flavor, and color as a result of quick heat transfer, (c) the removal of the hot heat transfer surfaces leads to minimum fouling depositions, since the piping applied is microwave transparent and remains relatively cooler than the product, (d) suitable for heat-sensitive, high-viscous, and multiphase fluids, and (e) high heating efficiency (Ahmed & Ramaswamy, 2007). Besides all of these advantages, there are some drawbacks, of which the most important one is lack of ability to control, predict, and measure the exact temperature at different part of the sample. Moreover, depending on several factors (e.g., nature of the food products, food geometry, dielectric properties, and oven designs), degradation kinetics of either quality, sensory, or nutrients could be observed (Zhang et al., 2001).

Ultrasounds: The advantages of using ultrasound for food processing, includes more effective mixing and micromixing, faster energy and mass transfer, thermal and concentration gradients decrement, temperature reduction, selective extraction, equipment size lowering, quicker response to process extraction control, faster start-up, production increment, and removal of process steps (Chemat et al., 2011). This technology, however, suffers from some drawbacks such as depth of penetration affected by solids and air in product, needs to be used in combination, potential problems with scaling-up plant with another process (e.g., heating) (Fellows, 2009).

Infrared processing: Major benefits of IR treatment could be listed as follows: high thermal efficiency, alternate source of energy, quick rate of heating, shorter response time, uniform drying temperature, high control degree of process, cleaner working environment, and possibility of selective heating. However, there are also some problems using IR processing such as low power of penetration and fracturing possibility of biological materials as a result of prolonged exposure (Krishnamurthy et al., 2008).

Ultraviolet and pulsed light processing: The advantages of UV treatment in comparison with other disinfection methods are very clear: no chemical application, a nonheat-related process with less changes in color and flavor, no residual in the fluid stream (Pereira & Vicente, 2010). A potential issue of this technology is its being harmful for human eyes and longer exposure may lead to burns and skin cancer in humans (Bintsis et al., 2000). Another limitation for UV usage may be the restricted range of commercially available equipment for disinfecting solids (Koutchma, 2008).

Concerning the benefits of PL treatment, although light intensity of PL is 20,000 times brighter than sunlight, quality and nutrient components are relatively retained (Brown, 2008). Comparing the applied lamps in PL (xenon-flash lamps) with UV method (mercury vapor lamps), PL is more environment friendly (Gómez-López et al., 2007). There are also some problems in using PL, for example, the presence of crevices or folds in food samples may result in microbial survival due to lower exposure to PL in these parts of the sample (Brown, 2008). Moreover, this technique is mostly applicable for liquid sample and surface of solid foods and thus limiting its usage (Abida et al., 2014). The most important issue about PL treatment is controlling food heating. For instance, Fine and Gervais (2004) reported undesirable color changes of the sample before microbial inactivation was completed due to thermal effect.

5 Conclusions

To produce food products with higher quality, emerging thermal and nonthermal technologies mentioned in this chapter hold great potential with higher energy efficiency compared to conventional methods. These novel technologies are applied in different segments of food industries to reduce the time and energy consumed during the processes. Current limitations (e.g., high investment costs) have been delaying a wider implementation of these methods at the industrial scale, which required more attention to be solved. Regardless of their challenges, it is obvious that these methods offer clear environmental benefits by enhancing the overall energy efficiency of the process or by lowering nonrenewable resources utilization.

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DRYING AND CHILLING/ FREEZING OF PERISHABLE FOODS IN THE ORGANIC SECTOR

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1 Introduction

Processing of foods is an important topic since 30% of the overall production of food is lost postharvest (FAO, 2013) because of lack of appropriate technologies and techniques for preservation. However, beyond avoiding losses, environmental impacts of processing should also be considered. While the primary production of organic products is well defined and strives for sustainability, the further value chain lacks clear instructions regarding organic processing. The processing steps for organic food are hardly of interest to consumers, who link organic products mainly to organic farming, but since the term “organic” stands for sustainability, the whole value chain from production over processing to packaging should be considered. Regarding quality aspects, food produced organically is often assumed to exceed conventional produce in terms of sustainability, which is not generally true and has to be considered differentiated from conventional produce (Tuomisto et al., 2012). Organic products are often thought to be produced more gently, a word that is not well defined in food processing. A high incentive for consumers to buy organic food, next to a resource-saving production, is the belief that organic products are healthier, which is not part of the discussion in this chapter. Nevertheless, some components such as secondary plant metabolites were investigated to be higher in organically produced fruits and vegetables (Asami et al., 2003; Carbonaro

et al., 2002; Dani et al., 2007; Young et al., 2005) and are worth maintaining during processing. In addition, the organic food sector should act as a pioneer regarding sustainable processing to decrease the environmental impact during processing, while producing a high-quality product.

Two important processing techniques can be stated as the most important in terms of a high impact on the product quality and energy consumption: drying and refrigeration treatments. Sustainable processing on the one hand retains the product quality, which means nutritional value, appearance (mainly color), flavor, and texture and should also guarantee microbiological safety and extended shelf life. In organic processing pretreatments are much more restricted than in the conventional sector and the processing steps are the main influencing factor for a high-quality product. On the other hand, processing consumes energy, often provided by fossil fuels. Sustainable processing should aim to reduce the dependency on fossil fuels to an acceptable level related to the processed output, and thus, increase the energy efficiency. In addition, processing of food could also influence the energy consumption during transport of the final product. Since nowadays there are possibilities to recover energy and to use renewable energy sources (RES), the aim of sustainable food processing can be realized.

Drying removes the water of fresh products to lower the moisture content to a level that minimizes deterioration processes. Regarding seasonal products it is important to extend the availability around the year and provide for storage without additional cooling. Drying requires specific process settings for every product to remain at high-quality with respect to different parameters, and has a big potential regarding energy saving, because today, a main problem in dehydration of organic products is the set-up of the production plants, which often work conventionally. For example, drying plants for food has an average energy efficiency of 35%–45% (Mujumdar, 2007) that leads to unnecessary high energy costs and food losses due to inadequate product quality, as inadequate conditions inside the dryer increase energy consumption and can influence quality parameters negatively.

Refrigeration is of great interest in the food industry and offers the cooling of food from ambient temperature to 0–8°C (chilling) or from –18°C to –35°C (freezing) to slow down deterioration processes significantly. Refrigeration has become more and more important as the way “from field to fork” increased due to a significant part of consumers, including consumers of organic food, settling in urban regions, which requires high product quality

and stability of perishable food products for extended periods. Chilling and freezing is less specific than drying but incorrect application leads to quality losses and unnecessarily high energy consumption.

2 Drying Methods

Drying is one of the oldest preservation techniques. However, dehydration consumes large amounts of energy to produce a safe and stable product. Drying in the sun is a cheap and easy method, but hygiene standards are often not achieved and drying times are long, which affects the quality of product negatively. Long drying times in sun result from relatively low product temperatures that reach max. 5–15°C above ambient air temperature (Grabowski & Boye, 2012) and can risk contamination with microorganisms and pests. Furthermore, it depends on the daily sun hours, which limits this method to sub/tropical countries and daytime. Dryers that are only based on solar energy, such as tunnel dryers, face similar problems but are in general advantageous in terms of hygienic conditions, because the product is protected from the environment. Solar drying can be very simple when it comes to methods such as cabinet or tent dryers, where the solar radiation is transformed into thermal energy and the airflow is generated by natural convection. Efficiencies of 11%–13% can be reached by these solar driers (Puiggali & Tiguert, 1986) and the quality of the final products was shown to be better, compared with sun drying, for example, regarding vitamin retention and increasing drying rates (Patil, 1989 cited by Grabowski & Boye, 2012). These constructions can be improved by the installation of solar collectors and fans to run them with higher drying rates. Pure solar dryers have a big potential for families or small-scale producers in developing countries, but regarding industrial drying, other energy sources have to be used to be independent of periods with low solar radiation. However, solar technology can be combined with conventional drying systems and offer a decent method for preheating the drying air, but is, in turn, limited to tropical and subtropical countries due to the yearly hours of sunshine, but can be a supportive measure in temperate zones.

Commonly used convective dryers (ca. 85% of industrial dryers) usually utilize the combustion of gas or oil or are based on electricity. Regarding fuel combustion the direct use of the developing heat in food drying is not recommended, because of toxic components in the exhaust gas. In addition, the amount of water as a by-product of combustion makes it difficult to reach

drying air of low humidity (Grabowski & Boye, 2012). Therefore, heat exchangers are used to heat the drying air that increases the energy efficiency and avoid pollutants of the fuel combustion to contaminate the product.

Further methods for food dehydration are microwave drying, vacuum drying, and freeze drying. While microwave drying is most efficient regarding energy consumption, it risks destroying valuable compounds due to high temperatures occurring inside the product. Therefore, regarding organic processing, microwave applications are not accepted for processing of products grown organically. On the contrary, vacuum and freeze drying need the highest amounts of energy. However, compared with convective drying, these drying techniques are technically sophisticated and have high investment costs, which makes an application very specific and only economically viable for valuable products. Osmotic dehydration is another drying method, but very specific regarding the raw material (intermediate moisture) and the final product.

2.1 Energy Saving Potential in Convection Dryers

Conventional dryers offer some options for energy saving as the process is studied more closely. As the energy consuming steps are evaluated and the drying time is reduced in a reasonable way, there is an energy saving potential for most drying processes used in food production to achieve a higher degree of sustainability.

2.1.1 *Efficiency Enhancement and Heat Recovery*

Convection dryers are very common in industrial food drying and as the consumption of fuel or energy is the main cost factor, development of energy saving measures has become necessary. Because the highest energy consuming step is the heating of the drying air, there are several possibilities to preheat the air. In many dryers the implementation of heat recovery systems directly from the dryer or by another technique is used (e.g., production of biogas) and can improve the efficiency in terms of using preheated air for the further drying process. Another possibility is offered by the position of the dryer as the surrounding air is preheated by the dryer itself, and the roof under which the dryer is located gives off heat by solar insolation. The usage of the surrounding, preheated air is then enabled by implementation of filters. A third possibility is the preheating of the air by the use of renewable energies such as wood.

2.1.2 Utilization of Renewable Energies

Organic farming pursues the idea of closed nutrient cycles, which also considers the production of RES on farms. Biogas was first implemented on organic farms to improve the waste management. Although biogas is in most cases not produced from waste materials anymore, it offers the possibility for fuel production for drying processes or at least the use of exhaust air as mentioned above for preheating of the drying air. The combustion of wood offers another option and can decrease the consumption of fossil fuels, and therefore, the CO₂ emissions for heating the drying air (Münsterer, n.d.). The application of heat pumps to a drying system has been described by Wang (2014) and has a large potential as they enable the use of energy at low levels, while increasing the energy level by low external energy input, which enables also the use of geothermal heat as an option to combine with dehydration processes.

2.1.3 The Impact of Optimized Air Velocities

As the drying process aims to transport the moisture out of the product by hot-air, it is important to adjust the air velocity during dehydration. Air velocities that are too high limit the contact time of the air with the product and therefore the water uptake, which leads to unnecessarily high energy consumptions. Low air velocities also lead to extended drying times as the drying air is saturated very quickly and cannot take in all the moisture evaporated. Therefore, the moisture covers the surface of the product and could induce changes in color and valuable substances. As the product remains relatively cold compared with the drying air, recondensation occurs.

2.1.4 Potential of Product Temperature Controlled Drying

Conventional process control is based on drying air temperature, which means that a product is dried at defined air temperatures. It is important to mention that regardless which air temperature is applied, the product temperature is not equal but lower to it, particularly in the beginning of the drying process, resulting from the difference between dry and wet bulb temperatures (Sturm et al., 2014). This becomes apparent when recognizing the drying curve of a hygroscopic solid dried under constant conditions. The evaporation from the surface results in a constant drying rate induced by capillary flow of fluid water (Aguilera & Stanley, 1999). This phase changes as the critical moisture content is reached that is specific and means that the drying surface becomes unsaturated. In addition, there are more than one

critical moisture contents possible that could lead to changes in the drying curve (Mujumdar & Devahastin, 2000). Sturm et al. (2014) showed that it is also worth considering the product temperature as a process control parameter, thus achieving reductions in drying times of up to 40%. Quirijns (2006) pointed out the development of gradients of quality indicators profiles (QIP), that is, moisture content and temperature inside the product during drying, which can be uniformed by changing the drying conditions during the process. Product temperature controlled drying needs relatively high air temperatures in the beginning to heat the product to the set temperature. Investigations on apple drying showed a much higher impact of dew point temperature and air velocities on drying kinetics and final product quality in drying air temperature controlled than in product temperature controlled processing (Sturm, 2010). Regarding the quality parameters color and shrinkage, product temperature control leads to fewer changes in both parameters. The information gained on product temperature enables a process setting with changes in air temperature during the drying process to improve the efficiency of the drying process and the product quality. Investigations on the advantage of step-wise drying were also done for potato slices (Chou & Chua, 2003; Chua et al., 2000; Ho et al., 2002), banana, and guava slices (Chua et al., 2000). In herb drying (*Melissa officinalis*), tests were conducted in terms of increasing temperatures after a certain moisture content is reached, with the best results regarding product quality when the temperature is increased at low moisture contents (Cuervo-Andrade & Hensel, 2016).

3 Refrigeration Methods

Artificial cooling was first noted in 1756, when Brit William Cullen published the method of cooling by the principle of evaporating of a liquid by negative pressure (Cullen, 1756). Although it was not successful economically, the principle of evaporation is similar to that used in modern cooling systems. Compression cooling techniques are well established in the food industry, but innovations with lower environmental impacts have gained interest (Tassou et al., 2010). Therefore, sorption refrigeration systems have been developed. Since the absorption technique is well developed, further techniques are under investigation to reach a higher energy saving potential (Tassou et al., 2010) and implementation of the usage of exhaust heat (Lambert & Jones, 2006; Wang & Oliveira, 2006). The performance of refrigeration units

is defined as the coefficient of performance (COP) and with <0.8 it is much lower for sorption applications compared with those of compression refrigeration applications of around 4 and is, therefore, interesting regarding sustainable refrigeration systems (Choudhury et al., 2013).

Since the 1930s, refrigerants with high ozone depletion potential (ODP) such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) have led to a dominance of vapor compression refrigeration cycle (Tassou et al., 2010). Their usage became a problem as far as leakages occurred in the systems and the gas entered the atmosphere. With the beginning of an increased awareness of environmental responsibility, the banning of ODP gases from the cooling industry began and the usage has not been allowed anymore in the European Union since the beginning of 2015 (Regulation (EU) No 517/2014 (2014)). However, it is not only the ODP that is critical regarding the usage of a refrigerant, also the potential for global warming (GWP) should be taken into account in the decision on an appropriate refrigerant with a low environmental impact. There are two groups of refrigerants that can be differentiated, natural ones and synthetic ones, mainly hydrofluorocarbons (HFCs). Table 1 shows an overview of common refrigerants without ODP and their GWP.

Table 1 Variety of Common Refrigerants With GWP

	Name	Technical Name	GWP ₁₀₀
HFCs	Flouroform	R23	14,800
	Difluoromethane	R32	675
	Pentafluoroethane	R125	3500
	1,1,1,2-Tetrafluoroethane	R134a	1430
	1,1,1-Trifluoroethane	R143a	4470
	1,1-Difluoroethane	R152a	124
Natural refrigerants	Propane	R290	3
	Isobutane	R600a	3
	Ammonia	R717	0
	Water/steam	R718	0
	Carbon dioxide	R744	1

Based on Regulation (EU) No 517/2014, 2014. Regulation (EU) No 517/2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006. Available from: <http://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32014R0517&from=DE>.

However, it should be mentioned that HFCs will disappear from industries in the near future, due to national and international restrictions in the course of climate protection.

Industrialized countries normally have an adequate cold chain where the different parts are controlled during production, processing, transportation, and storage. However, [Hemmingsen et al. \(2004\)](#) indicate based on different studies and measurements that the segments of transport and sales are challenged in view of holding the required maximum temperature of the cold chain. This includes errors and lack of chilling in transfer operations or transport equipment.

4 Quality Parameters

The quality parameters of processed foods aim to be similar to those of fresh produce and strongly depend on: the right timing of harvesting (overripeness) and the time between harvest until the beginning of processing, for both heat and refrigeration treatments, and on the applied processing itself. The most important quality parameters are microbial safety, appearance, sensory attributes, and nutritional value.

4.1 Dried Produce

Dehydration aims to reduce the moisture content of fresh products and at the same time bring the water activity (a_w) to a level that inhibits microbial growths (<0.6). Besides microbial stability, it is essential to preserve the cell structure, and therefore, the cytoplasm as most reactions take place there ([Bai et al., 2002](#); [Lewicki & Pawlak, 2003](#); [Mayor et al., 2005](#)). This means not to overheat the product during the process and to avoid unnecessarily long drying times. Most food products are dried at temperatures between 50°C and 90°C, relative air humidity of 10%–40% and air velocities of 1–4 m/s, but depending on the combination of those parameters, the quality of the final products will differ greatly ([Krokida & Maroulis, 2000](#)). Organic processing is often limited to lower temperatures that in turn affect quality parameters. Even if it is not possible to avoid changes in product size, shape, and valuable substances, the drying process should be adjusted to maintain the properties of the raw material as much as possible. As the components have different critical temperatures, losses will occur to a smaller or larger extent. Nevertheless, many losses can be avoided by using modern control systems. It is essential to investigate and understand chemical and physical

processes inside individual products during processing to adapt and control the process during drying to gain high-quality dried products.

4.1.1 *Appearance*

The shrinkage of a product is mainly affected by the drying temperature, and thus, the rate of water removal. It is less extended at high temperatures due to the fast drying, and thus, the preservation of the surface (Aguilera & Stanley, 1999). In addition, high temperatures can lead to case hardening induced by soluble components that develop a crust on the surface. This can lead to longer drying times as the case hardening acts like a barrier regarding evaporating moisture from the inside. In addition, it can prevent the loss of large aromatic components that remain in the product through case hardening (Thijssen, 1979). Browning of the product during dehydration may occur due to enzymes such as the polyphenol oxidase (PPO) in apples. As many enzymes are not stable to heat, enzymatic browning can be avoided by high drying temperatures or pretreatments such as blanching. In addition, sugars and proteins undergo changes induced by high temperatures (denaturation of proteins) that can lead to nonenzymatic browning (Maillard reaction) and consequently influence the sensory attributes, the appearance and the nutritional value. Other nonenzymatic browning reactions are caramelization of carbohydrates that can occur during drying under high temperatures and the oxidation of ascorbic acid that can occur during processing or storage under aerobic and anaerobic conditions. Changes in color may also occur due to degradation of pigments such as chlorophyll (green), carotenoids (orange, yellow), anthocyanins, anthoxanthins, and betalaines (red to blue). In this case, it strongly depends on the product and on the drying process as to how well the pigments are retained, as it was shown by Negi and Roy (2000) for savoy beet, amaranth, and fenugreek dried under different conditions.

4.1.2 *Sensory Attributes*

The shelf life mainly depends on a low moisture content between 2% and 20% (Kader et al., 2002) and a water activity (a_w) below 0.65. However, products high in protein and fat content always require a particular processing to avoid the development of rancidity, and therefore, off-odor and -taste during storage.

Protein denaturation leads to the release of amino acids, where free lysine is an amino acid used as an indicator for the degree of protein degradation (Bolin & Steele, 1987). During the drying

process proteins can be affected by enzymatic degradations and lipids by enzymatic hydrolysis that can lead to changes in taste (Perera, 2007).

4.1.3 Nutritional Value

Many components in agricultural products are sensitive to heat, especially fruits and vegetables that are rich in vitamins and secondary plant substances that can be destroyed by high temperatures or by enzymes during the early stage of drying, which lowers the quality and health benefits of the product.

Vitamin C is relatively heat instable and in addition is prone to oxidation by ascorbic acid oxidase, while B vitamins (e.g., riboflavin, niacin) are more likely to be lost during pretreatments such as blanching (Perera, 2007). On the contrary, Vitamin C retention is higher when the drying period lasts shorter (Goula & Adamopoulos, 2006). Vitamins A and D are more prone to enzymatic oxidation than losses caused by heat. Thus, in the case of heat instable vitamins, organic processing at low-temperatures retain the vitamin content, while low-temperatures do not inactivate vitamin destroying enzymes.

4.2 Chilled/Frozen Produce

Chilling and freezing provide a good possibility to retain the initial quality status of the raw product. The loss of water due to evaporation is reduced and the mechanical strength, especially in freezing, is increased. The refrigerated products remain fresher and show less bruise and damage. Chilling temperatures (0–15°C) are very specific for most products and can extend the product quality from a few days to several months as long as the product is not damaged or sliced. Both scenarios would enable microbial or the products own deterioration processes, causing the spoilage of the product very quickly. In addition, slicing increases the product surface and therefore the ability for oxygen to oxidize valuable compounds. For long-term storage and even storage of sliced products, freezing is more appropriate.

However, there are vegetables, which are not appropriate for freezing or at least do not have the properties to retain quality after thawing. This includes for example lettuce or mushrooms, while usually most fruits and vegetables retain their quality parameters to a high degree. Products of high water content are known to lose water during thawing, which can, depending on the amount of water, influence the product quality negatively. Negative effects in product quality occur due to ice crystals formation during the

freezing process inside the product that damage the cell structure. The more water a product contains, the higher is the temperature at which the product begins to freeze. It is important to reach the final temperature for storage very quickly by blast freezing and to pass the critical temperature range of temperatures between -0.5°C and -5°C quickly, where the formations of ice crystals is highest.

Each freezing step aims to produce the smallest ice crystals possible, that do not damage the cell structure and therefore make the process reversible. The formation of big, extracellular ice crystals leads to significant damages of the tissue (Kiani & Sun, 2011) and are associated with slow freezing. While thawing, the formation of big ice crystals result in high losses of water as a consequence of damaged cells, and therefore, valuable compounds.

In industry, the product is usually frozen before it is stored at a final temperature. A cooling tunnel provides the best option to freeze the product at low air temperatures, a freezing step using nitrogen is also common. Nitrogen shows a big advantage due to high cooling rates and short freezing times, but is relatively expensive. In contrast, the usage of the cold storage for the freezing step provokes an inadequate product quality as the cooling load of the raw product is too high for adequate freezing and results in the formation of big ice crystals due to a very slow freezing of the product.

The safety of a frozen product can be affected negatively when it comes to thawing. As pathogens are not killed by freezing, it is necessary to thaw the product at a temperature of around 4°C , which leads to a slow thawing at low-temperatures and does not influence the microbial growth. A quick thawing, for example, in warm water, provides optimal conditions for microbial growth and therefore endangers the safety of the product.

5 Case Studies

5.1 Herb Drying

The production of high-quality herbs is a big challenge in organic production. Our own investigations showed big differences between herb farms regarding energy consumption and product quality. The cultivation as well as the drying step takes place in a decentralized manner on farms to gain optimum product qualities, as the processing has to be conducted as soon as possible after harvesting. Organic herbs are mainly used as medical plants and spices, and therefore, have to meet different quality

standards after drying such as the microbial safety at a moisture content of maximum 10%, the essential oil content and the color. However, organic herb drying is restricted to low-temperature drying (30–40°C), and therefore, could lead to problems regarding energy consumption and product quality.

5.1.1 Herb Drying Techniques

The drying techniques for herbs are limited and in Germany herbs are often dried with 3- or 4-floor kilns, and belt-, and batch dryers. In the United States 1-floor kiln dryers are more common for drying of aromatic plants such as herbs and hops (Hofmann et al., 2013). The usage of kiln drying leads to several drying steps, beginning with fresh herbs on the top tray, one or two middle trays below and the slip case (Fig. 1). The time point for tipping can be controlled by the relative humidity of exhaust air and could be improved by determination of the moisture content of the product.

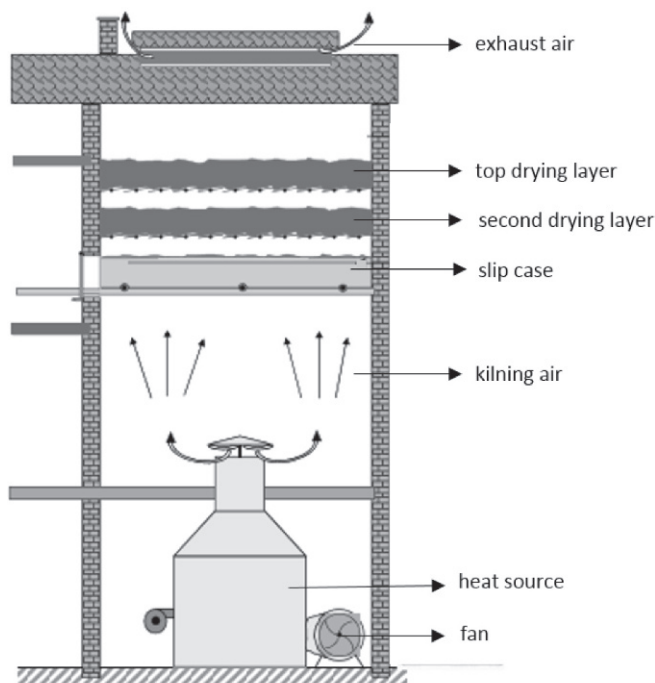


Fig. 1 Schematic diagram of a 3-floor kiln dryer. Adapted from Münsterer, J., 2006. *Optimale Trocknung und Konditionierung von Hopfen*. Available from: https://www.lfl.bayern.de/mam/cms07/ipz/dateien/hopfen_p_23593.pdf (Accessed 13 January 2017).

5.1.2 Microbial Safety

Producers of herbs always face risks with molds, yeasts, and bacteria, as both the environmental air and the short distance from soil risks a preharvest contamination. Furthermore, a microbial contamination is much more likely when food sanitation is poor as it can be found in many developing countries (Schweiggert et al., 2007). The drying process has to reduce the microbial activity, reduce microbial growths during drying to a minimum, and avoid the development of spores. Herbs are often used as additives in processed foods and can present a hidden danger regarding microbial spoilage once the dried herbs are used in water-rich food products, which is a problem when adding them to “ready-to-eat” products without additional heating before consumption (Little et al., 2003).

Many processors face problems with microorganisms, which are close to legal limits for microbial infestation, but also a contamination with human pathogens such as *Salmonella* or *Bacillus cereus* are possible (McKee, 1995). In the United Kingdom, Sagoo et al. (2009) investigated retail samples and production batches of herbs whereas 3% showed a high count of pathogens. Sospedra et al. (2010) showed a poor microbial quality for herbs sold in Spanish markets where in 20% of the samples enterobacteria and at lower amounts other pathogens have been found. Next to deterioration of the product, and therefore, the lowered quality, toxins such as aflatoxins from molds bear a health risk. As aflatoxin was found to be heat stable (reviewed by Bullerman and Bianchini, 2007), it creates a hazard in both “ready-to-eat” and heated products.

Therefore, the challenge organic herb producers face is the low-temperature drying process, which has to guarantee a safe product and a high retention regarding other quality parameters. Usually, a significant microbial growth is avoided by the reduction of the drying period that offers optimal conditions, for example, moist and warm, especially in the first phase. Optimum temperature for microbial growth is around 37°C, while the relative humidity has an optimum at above 70%.

Thus, it is very important to remove the humidity from the product that occurs from evaporation during drying by an appropriate air flow, and therefore, to avoid auto-heating due to respiration activities, that can also occur during storage before the drying begins (Müller, 2007). Under “state-of-the-art” conditions, the microbial count is not significantly increased during the drying process (Müller & Heindl, 2006) as was also shown by own observations. However, often problems regarding ventilation

and bulk densities can be investigated on farms, which inhibit the reduction of microbial activity or, even worse, significantly increase the microbial growth during the drying process. Own investigations showed increasing microbial loads at increasing bulk heights, which lead to increased drying times and to long periods under warm and moist conditions inside the bulk, which can be improved by increased ventilation. Low airflows support optimum conditions, extend drying times and, therefore, increase the problem of microbial growth, while high airflows lead to the risk of nest formation due to swirled up herbs with the consequence of higher moisture contents inside those nests after the drying period. This indicates the necessity of appropriate air velocity setting at different stages of the drying process, also with regard to reducing energy demands. However, low-temperature drying has the potential to keep the microbial load at an acceptable state in organic processing as appropriate humidity and velocity settings of the drying air support suitable drying conditions.

5.1.3 Essential Oil Content

The influence of drying on volatile compounds (essential oils) was investigated in several studies. Independent from low energy consumptions, microwave drying is not useful for herb drying as the leaf structure is affected by the microwaves (Yousif et al., 1999) due to high temperatures that result in collapsing of the cells and justifies the restrictions for the use of microwaves in organic processing.

As diverse as herb varieties are, so diverse are the studies that are available regarding herb drying. Many studies showed that increasing losses of essentials occur at increasing temperatures (Müller, 2007). This fits with the idea of gentle processing in organic food processing, and drying temperatures between 30°C and 45°C can be found on many, organic and conventional, herb processing farms. Low-temperature drying for herbs can be provided by shade drying but requires constant, relatively high outdoor temperatures, and thus, is not appropriate in temperate zones. Regarding convective drying, which is most common for industrial drying of herbs, even air temperatures above 30°C have been determined to reduce essential oil content of herbs significantly as it was shown for example for peppermint (Rohloff et al., 2005) or wormwood drying (Khangholil & Rezaeinodehi, 2008). Ghasemi Pirbalouti et al. (2013a) investigated different drying methods for basil and demonstrated the clear advantages of shade drying compared with sun drying. As the losses of volatile

compounds were comparably high, as in microwave drying, it once again indicates the potential for solar application to sustainable processing systems and the unsuitability when applied directly, where both, the heat from absorption of the solar radiation and the deterioration, may be responsible for losses of volatile compounds.

The retention of essential oil was investigated very high for freeze dried basil, whereas significant losses in oven drying at 40°C, and therefore, bigger losses for oven drying at 60°C have been found (Ghasemi Pirbalouti et al., 2013a). However, these results do not seem to be valid for all varieties of herbs. In a very similar study, Ghasemi Pirbalouti et al. (2013a,b) investigated different drying methods for Bakhtiari savoury (*Satureja bachtiarica* Bunge), a traditional Iranian herb, with the highest oil yields for samples dried in an oven at 45°C and freeze drying. Even oven-dried samples at 65°C had higher essential oil contents than shade-dried samples, which showed similar oil contents to sun dried samples. The results were similar in thyme drying, but sun drying gained the same high oil yields such as oven drying at 50°C (Rahimmalek & Goli, 2013). While for basil freeze drying results in high retention of essential oil content (Ghasemi Pirbalouti et al., 2013a), it was reduced under these drying conditions for Bakhtiari savoury (Ghasemi Pirbalouti et al., 2013a,b). This might be due to the processing below atmospheric pressure and has also been shown for vacuum dried lemon balm (Argyropoulos & Müller, 2014a).

Contrary to the results of those studies, there are also investigations that show a higher retention of essential oil content at increment of air temperatures in convective drying. Müller and Heindl (2006) stated sage dried at 50°C air temperatures to be without losses in oil content, while it was reduced at 90°C. Toriki-Harchegani et al. (2016) dried peppermint at 50°C, 60°C, and 70°C and found the highest amount of essential oil for the samples dried at 70°C, which they explained with a shorter drying time compared with 50°C and 60°C. Arabhosseini et al. (2007) even found the highest yield of essential oil in tarragon dried at 90°C. However, the highest retention during storage was investigated in tarragon dried at 45°C.

The results of different studies are hard to compare as the experimental conditions differ between the studies. In most studies, the air temperature is connected directly to the retention of volatile compounds. However important information regarding drying conditions such as bulk density or air velocity is missing. This affects the results significantly and leads to very different drying times for similar products. For example, basil took 50 h at air

temperature of 50°C, which is very long while the moisture content was still above 10% (Ghasemi Pirbalouti et al., 2013a), while peppermint reached a stable moisture content already after 5 1/2 h at 50°C (Torki-Harchegani et al., 2016). The peppermint was dried with an initial bulk height of 10 mm and a constant air flow of 0.4 m/s while there was no information for those parameters for basil.

The loss of essential oils is directly related to the moisture content. Argyropoulos and Müller (2014b) investigated that the main losses of essential oils that occur at a moisture content of more than 50% and significantly increases when the temperature is over 45°C for lemon balm. Even the first 30 min at 60°C lead to losses up to 45% of essential oil. The authors described a relatively low bulk weight of 2.2 kg/m² and a ventilation of 0.2 m/s. However, the relative humidity of the drying air was different for the different temperatures. The study furthermore showed that overdrying does not affect the content of essential oil significantly. However, overdrying results in unnecessarily high energy consumption. Organic herb drying at low-temperatures has, therefore, to enable adequate ventilation to reduce the moisture content as fast as possible to achieve conditions inside the product that reduce losses of essential oil until a stable moisture content is reached and reduce energy demands.

5.1.4 Color Changes

Color is a very important quality parameter regarding consumer acceptability. Processing strives to influence the color of a product as little as possible compared with the raw product. In herb drying, the color can be affected by the heat as well as by water vapor that is removed in an insufficient way due to high relative humidity or low airflow inside the dryer.

Rahimmalek and Goli (2013) found the best retention in lightness for a thyme subspecies dried at 50°C, with similar results in shade and microwave drying. Greenness was significantly affected by oven, freeze, solar, shade, and microwave drying whereas oven drying at 50°C and 70°C showed the worst results as the negative a^* values from fresh thyme even changed to positive values. Shade drying showed the best results for greenness, which indicates advantages of low drying temperatures applied in organic farming. The changes in greenness occurs due to degradation in chlorophyll, which is reported as not heat stable (Weemaes et al., 1999).

For drying of Melissa, Cuervo-Andrade (2011) found the lowest change in color for drying at 40–45°C and reasoned the higher

color change at 30°C by the extension of the drying time, which effected the color negatively. The relative humidity also can influence the color change, as at 7% the color change was bigger at 60°C than it was at 18% for the same temperature (Arabhosseini et al., 2007). In general, the studies mentioned support a low-temperature application for organic herb drying to achieve acceptable color changes, but once more indicate the necessity for product specific drying, reduced drying times and proper removal of saturated air by ventilation.

5.1.5 Energy Consumption

The drying process also influences the environmental impact as reduced drying times lead to less energy demands. The drying of medical plants represents 30%–50% of the total production costs and, is therefore, to be regarded carefully in terms of the energy saving potential (Qaas & Schiele, 2001). Own investigations showed big differences regarding energy consumptions on organic herb farms with differences of 5000 kWh per ton dried products (min. 8000 kWh, max. 12,600 kWh) for the same herb varieties (spearmint, peppermint). The reasons for different energy consumptions were diverse such as bulk density, air flow and also preprocessing such as the removal of the stem. The development of individual drying processes in terms of variety, initial moisture content and product parameters are unavoidable to gain efficient drying processes and high product qualities.

The optimum temperature and drying conditions have to be evaluated for different plants and could lead to significant energy reductions as investigated for sage by Müller and Heindl (2006), who increased the drying temperature by 5°C from 45°C to 50°C, which resulted in a decrease of drying time by 60% and the energy consumption by 35%. The best results in terms of energy consumption regarding different drying methods have been observed for microwave drying, followed by air drying and high amounts of energy consumption for vacuum drying in drying of nettle leaves (Alibas, 2007). The author also observed lower energy consumptions at increasing drying temperatures. Toriki-Harchegani et al. (2016) compared microwave drying and hot-air drying at different temperatures. The drying time for microwave drying can easily be expressed in seconds whereas in oven drying the expression in minutes or hours is more appropriate, which shows the large difference between microwave and oven drying. However, as the use of microwave drying is disadvantageous regarding heat sensitive compounds such as essential oil (which is reduced to a minimum in peppermint

([Torki-Harchegani et al., 2016](#))) and is therefore, despite low energy consumption, justifiably not an alternative drying technique for organic processing. In addition, high investment and maintenance cost have to be considered.

[Fatouh et al. \(2006\)](#) investigated the adaption of a heat pump to a convection dryer for Jew's mallow, parsley, and spearmint and observed decreased energy consumption of up to 15% compared with conventional convection dryers due to an efficient recovery of consumed energy ([Patel & Kar, 2012](#)), which shows the potential for the usage of RES. In addition, our own investigations showed a potential in sorting of stems. This is due to higher moisture content and different structure of the stems, which leads to longer drying times.

A further parameter that influences quality parameters and energy consumption is the bulk density that is defined as bulk weight or bulk height per drying area. This becomes obvious in our own investigations on organic herb drying where the energy consumptions differed. It was found that at low bulk densities the air velocity has a minor impact compared with high bulk densities in sage drying, which is reasoned by fast saturation of drying air at high bulk densities ([Müller & Heindl, 2006](#)). Low air velocities result in high relative moisture contents inside the dryer that can substantially increase the drying time. However, experimental work is barely comparable to practical field work, which means that farmers have to make compromises regarding bulk weight and energy consumption as the processing is time intensive and an appropriate portioning of the full harvest is not always possible. As organic herb production is often done by small holders, the drying capacity can be very small. Higher bulk densities can increase it, when air velocities are adapted at the same time to reach optimum drying conditions.

5.2 Superchilling as an Innovative Refrigerating Method

Organic consumers expect high-quality products from the cold chain, which fulfill health and security requirements in the supply chain. Particularly, the producing and processing industry in the cold chain are facing challenges during preservation and distribution of fresh perishable products. The most important factors for the quality of chilled and frozen products are storage temperature and time, which directly influences the shelf life and quality.

Trade-offs in refrigeration are that chilling consumes less energy but provides only short-term storage for fresh produce

and freezing is appropriate for long-term storage but is consuming high levels of energy. The aim of providing high-quality products with extended shelf life at relatively low-energy levels led to the idea of superchilling in the recent years. Superchilling combines both chilling and freezing, whereas only 5%–20% of the water inside the product is frozen (Kaale et al., 2011), but the product appears unfrozen. However, the amount of water in frozen state is not well defined yet and is specific for every product and ratios of frozen water up to 30% can be found in research studies. At the beginning of the investigation of the technique the FAO reported about superchilling in the fishing industry and stated 50% of the water at frozen state (Waterman & Taylor, 2001). Supercooling is another cooling technique for food products, which is different from superchilling as there is no formation of ice crystals inside the product, although it is stored below the initial freezing point of water.

The concept of superchilling used the phenomenon of freezing point depression of water inside a food matrix which freezes at lower temperatures. Food matrixes have been found to contain liquid water even if the temperature is below -20°C (Valentas et al., 1997), which is contrary to pure water that reaches lower temperature only after all liquid water is in the frozen state.

Every product has a specific temperature at which a predefined amount of the water inside the matrix is frozen and if the product is stored at this specific temperature, it will gain superchilled status with water in liquid and frozen state, occurring as little ice crystals throughout the product. However, gaining the superchilled status only by storage at superchilling temperature leads to long processing duration due to the limited heat transfer by the low-temperature difference between product and ambient air temperature.

Superchilling might have potential for organic produce especially in countries where specific organic markets are comparatively small. The organic meat market in Norway for example is small and only half of the organically produced meat is sold under the organic label. The reasons for this are not investigated in this project. However, during discussions with small producers it became clear that valuable time is lost in the cold chain between slaughtering, processing and packaging before the product is ready to reach the market. In some cases, small producers do not have the infrastructure/possibility to slaughter on site and they need to send their animals to certified slaughterhouses. After slaughtering, the unprocessed raw meat is sent back to the producers for further processing and/or packaging and labeling and can then be sent out to the retailer. The organic meat is,

therefore, a few days old before the consumer has the possibility to purchase it because of the distances, place of production and time necessary for transport and processing. Consequently, the organic meat is already exposed to quality reduction compared with traditionally produced meat in the supermarket. It can be estimated that the postpurchase shelf life of organic meat is reduced by 50% for certain cases when compared with conventional meat. Possibilities to extend the shelf life and improve the quality of organic meat would help the producers to be more competitive in the market. It would also enable local producers to reach far distance markets, which are currently not exploited due to transportation time.

5.2.1 *Improvement of the Superchilling Process*

To decrease the processing time of superchilled products, the method of fast initial shell freezing using a conventional blast freezer at -40°C before storing the product at superchilling temperatures can be used. After this step, the predefined amount of water related to the product in a frozen state is gained before storage. This technique is based on first freezing the outer layer of a product, which takes a time of 1–3 min, related to size and product. The freezing time is relatively short, due to the increased heat transfer compared with the above-mentioned technique at storage temperature. Again, this step is very specific for each product and different parameters such as the product itself, size and heat transfer coefficient have to be taken into account to gain the correct degree of ice formation. The following storage only has to sustain the specific temperature to retain the state of superchilling and to ensure that no heat load is created for ice formation. [Fig. 2](#) schematically shows the steps of the superchilling process.

During storage the frozen outer shell disappears as the distribution of the ice crystals begins until it is evenly distributed throughout the whole matrix, resulting in a fresh appearance, while the temperature is below its initial freezing point. The appearance of the product is still like an ordinary refrigerated product and it is not possible to feel or see the present ice fraction. [Bantle et al. \(2016\)](#) investigated initial freezing points of -1.6°C for salmon filet, mackerel and herring. However, while the ice formation of salmon and mackerel were similar at different storage temperatures, it was different for herring ([Table 2](#)), which indicates the specific temperatures for the superchilling process for different products.

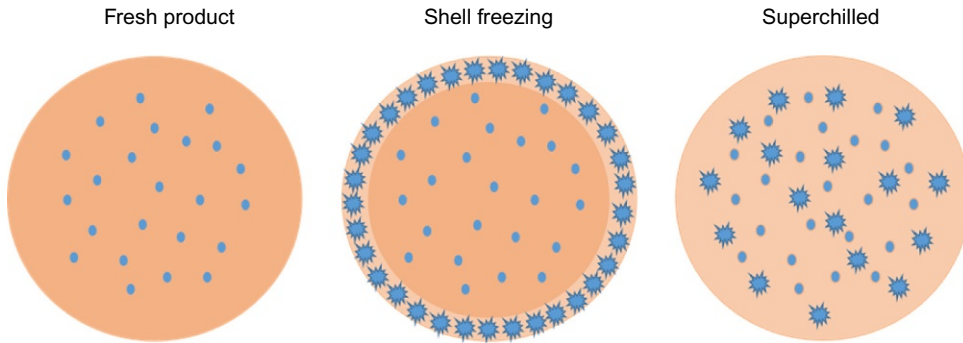


Fig. 2 The different steps in superchilling of food: The present water in the product is partially frozen and after a certain time mixture of water and ice is present inside the structure of the product.

Table 2 Relation Between Storage Temperature and Ice Fraction for Salmon Filet, Mackerel, and Herring

Product	Superchilling Temperature (°C)	Ice Fraction (%)
Salmon filet	−1.8	6.3
	−2.2	18.2
	−2.6	26.9
Mackerel	−1.8	6.3
	−2.2	18.2
	−2.6	26.3
Herring	−1.8	4.0
	−2.2	11.6
	−2.6	18.7

Adapted from Bantle, M., Nordtvedt, T.S., Claussen, I.C., Indergård, E., 2016. State of the art: superchilling in the food processing industry. In: 4th IIR International Conference on Sustainability and the Cold Chain-Proceedings, International Institute of Refrigeration, Editors.

5.2.2 Quality Evaluation of Superchilled Products

The technique of superchilling shows good results for meat products of mammals and fish. Compared with traditional refrigeration the storage of superchilled products is around 5–10 K lower. Investigations showed shelf life extension of 14–21 days depending on the product while also other factors such as processing hygiene, mechanical stress, and so on may have an influence. As drip loss is an important quality parameter regarding meat

products, several studies indicate no negative, or even a decreased effect in superchilled products. Superchilled cod filets were compared with traditional chilled ones (Duun & Rustad, 2007). Although the low-speed centrifugation showed an increased drip loss, which might be due to protein denaturation induced by freezing, the normal drip loss was reduced compared with the chilled cod filet. Further investigations might improve the superchilling step and therefore might reduce the protein denaturation. Similarly positive results were gained for vacuum packed pork roast (Duun et al., 2008). After 16 weeks of superchilling storage at -2°C the sensory attributes were unremarkable, and drip loss was lower compared with chilled pork roast stored at 3.5°C . In addition, the application of a stable temperature during storage was regarded as parameter to gain optimum product quality. Regarding microbial growth, it might also be possible that the blast freezing before the storage might have an influencing effect as the low-temperature stop the microbial activities on the surface and may also partly destroy bacterial activity (Magnussen et al., 2008). For salmon storage temperatures for superchilling of -1.4°C and -3.6°C were investigated (Duun & Rustad, 2008) and compared with chilled ice storage. The storage time of chilled salmon of 17–21 days was doubled, but did not lead to higher amounts of drip loss. Both superchilling temperatures were not appropriate as the storage at -1.4°C showed an increased textural hardness and at -3.6°C increased protein denaturation. This again indicates that a thorough evaluation of the proper storage temperature is necessary. Next to quality aspects another Norwegian national study (Norwegian Research Council, 2016) concentrated on energy consumption. Although the drip loss of lamb was increased, the pH and color of the meat was stable and the shelf life increased compared with chilled lamb. Furthermore, the energy demand was reduced by 13% compared with completely frozen lamb. Friestad (2014) stated that the freezing damage of superchilled lamb is lower compared with frozen lamb and higher compared with fresh lamb.

5.2.3 Superchilling in Organic Processing—Chances and Challenges

The additional processing equipment and modified storage conditions for superchilled products can be a barrier for the implementation for small-scale producers who can often be found in the organic sector. However, innovative new solutions are often implemented in small or medium-sized production facilities, since the production is more flexible and the market

potential is more promising for these producers. A big potential can be seen in the increase of shelf life, as the production is not always close to potential markets and long geographical distances have to be covered. Consequently, the organic products can compete when it comes to shelf life and quality in the supermarkets, even when conventional large-scale producers have a better-developed (and faster) distribution network. Organic production strives for avoidance of food losses. If superchilling is implemented in the early stage of fish processing, bigger product yields can be reached due to advantageous conditions in post slaughter steps. However, skinning of fish is negatively influenced by superchilling (Stevik & Claussen, 2011). Organic farms are often based on the principle of direct marketing; however partial overproduction of a specific product can occur. Usually, overproduction is frozen to gain a stable storage and a future sale, with the disadvantage that it consumes much more energy than chilling. Therefore, the profit of fresh products is higher due to lower storage costs. Superchilling would enable the substitution of freezing perishable products and in this context gain a profit closer to fresh products. Superchilling may also reduce the environmental impact of transportation of chilled products. In case of high-quality fish, the fish is stored on chilled ice to maintain the quality. This results in up to one-third ice of the overall transport weight, while the rest is the weight of the product. This increases the transport cost and results in higher CO₂ emissions and furthermore results in less efficiency as more transport units have to be used. Superchilling would enable higher amounts of valuable product to be transported in less transport units. As the ice inside the superchilled product acts as a thermal inertia a transport under chilling temperature is sufficient. Although it will reduce the shelf life compared with products stored under superchilling conditions, due to a reduction of the ice inside, it will have a longer shelf life than products that are transported under a chilled state. Compared with conventional chilling, superchilling is much quicker which can make a production line more efficient. This is reasoned by the fact that the product is prechilled directly during blast freezing which might increase capacities of production lines.

Until now superchilling is only used in a few Norwegian processing lines for fish and meat products but not in other food markets. This might be due to the valid standards in which an innovative processing technique is hard to implement, particularly because the final product is neither chilled nor frozen, but at a state between. Already more than 15 years ago the FAO indicated that the food labeling legislation does not permit the sale of a thawed product as fresh (Waterman & Taylor, 2001), even if the

quality parameters are closer to fresh products than to frozen/thawed products as in the case of superchilled products. As organic standards are even stricter, implementing superchilling into organic processing might be an even bigger challenge. However, it is a technique worth considering. A main factor to achieve optimum product quality is the correct calculation of time for initial blast freezing and the correct storage temperature, whereas the temperature distribution inside the product is of high priority to avoid an excessive degree of ice formation. Otherwise, incorrect temperature application, even on a minor scale, can lead to increased ice formation, and consequently, to lower product quality due to higher freezing damage inside the product. Future investigations will lead to improved calculation models to be able to compensate for different shape and product size of the raw material, and therefore, improve superchilling. Furthermore, the specific ice content of different products has to be defined. As mentioned above, in general the ice content is 10%–20%. However, this span is relatively large and can affect quality parameters such as drip loss negatively. The storage temperature is much more crucial in terms of destruction of pathogens and microbial growth. The implementation into industry requires effective and flexible processing equipment, which might be even more of interest in SMEs like many organic processors are. Another challenge might be the consumers' acceptance, which might be a bigger issue for the organic than for the conventional food sector and should be taught carefully, as new processing methods might be recognized as critical in terms of food quality and sustainability.

6 Conclusion and Outlook

Sustainable processing should be a firm component in organic production, as the primary production of organic products on farms strives for low environmental impact and high product qualities that should be continued throughout the further value chain.

Drying and refrigeration techniques are often identical to those used in conventional processing. However, in food dehydration, applied processing temperatures are decidedly lower due to restrictions, particularly when specific standards of organic associations are applied. Long drying times and low-temperatures are potentially challenging in terms of microbial product quality and energy efficiency of the process. The application of high air velocities at the beginning of the drying can positively affect the overall efficiency and resulting product quality. The removal of the

moisture from the product surface by appropriate air velocity is a key parameter that is often neglected whereby it can improve the drying process significantly due to reduced drying times. Furthermore, there is a large potential for individual process settings based on product temperature to maintain high levels of valuable compounds of the product and reduce the energy demand. Through the application of product temperature as control variable, the drying process becomes more efficient and less time consuming, whilst guaranteeing for the product to not exceed its critical temperature limit.

Step-wise drying can lead to reduced drying times and thus lead to lower energy consumption and higher product quality in terms of microbial stability, volatile compounds, and appearance. The usage of heat from exhaust air and renewable energies provides additional opportunities for both, heat and refrigeration treatments, to reduce the environmental impact. The economic viability of renewable energy integration however, decidedly depends on the type of products processed and their combination. Seasonal processes are not suited for RES integration other than potentially biomass in form of wood or wood chips.

Refrigeration treatments do not differ in organic processing compared with conventional. However, refrigeration applications can be adapted to the sustainable concept. Such as the decision to use natural refrigerant substitutes as opposed to the usage of refrigerants with global warming potential for organic processing. Besides conventional cold storage such as chilling and freezing, investigation in superchilling can provide a big potential regarding product quality, whereas, the shelf life of fresh products can be extended at lower energy consumption and higher product quality compared with freezing. However, this innovative processing technique is not licensed yet, but is interesting in terms of the provision of fresh products to long-distance markets as this is often found difficult for organic smallholding farms and processors.

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SUSTAINABLE PACKAGING

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1 Introduction

Food packaging materials are traditionally nonrenewable ones, except for paper-based products. In effect, fossil resources could be considered as bio-based and renewable materials but it takes more than a million years to convert biomass into oil used for plastic production. Since the use of crude oil is faster than the replacement of biomass, an imbalance in the carbon cycle is recorded.

From the beginning of the 20th century, increasing interest is being given to environmental concerns, racing the replacement of petrochemical-based resources by biologically derived resources. Plant-derived products and by-products obtained from their fermentation were the most interesting candidate for plastics packaging production. Such products, named bio-based packaging materials, have been defined by Robertson (2013a) as “materials derived from primarily annual renewable sources.” Starch and cellulose films, polymers obtained from fermented organic materials together with edible films and coatings are included in this definition. At present, the term bio-based plastics means plastics obtained from bio-based materials. Both academia and industry are interested in such materials but their commercial use is still in progress with the hope that in the next decade the situation will change (Peelman et al., 2013). In 2010, the consumption of bio-based packaging materials was about 125,000 tonnes, very far from the 100 million tonnes of petrochemical-based plastics used for the same packaging purpose (40% of the 250 million tonnes produced every year). It takes many years to replace petrochemical plastics with bio-based materials. The driving force of this development could be the interest for a more sustainable packaging industry. Solid waste and litter problem together with the terrestrial and

marine environmental pollution coming from the use of plastic materials could be the key of the bio-based packaging materials development. Since the production of packaging represents one of the most consistent causes of material-related environmental impacts, innovative tools have been designed for improving the environment as well as the economic performance of packages. At a global level, there is a strong interest in bio-based materials as a tool to address the food industry needs, to control the production chain, first of all by reducing material wastes. The aim is to assess and consequently reduce the environmental impact associated with the production, use and disposal of food packaging materials. In particular, edible, bio-based, and biodegradable materials obtained from renewable resources are driving ambitions to replace the packaging materials, coming from nonrenewable resources, to achieve a more sustainable development of the packaging industry.

2 Packaging Materials in the Food Industry

Various shapes of packaging materials are present in the food market, with a wide range of functions correlated to their properties. As reported in [Fig. 1](#), a good balance between shape and function is required.

Taking into consideration that the most important feature is to preserve, contain, and protect food during the whole shelf life, the choice of the most suitable packaging material is dependent on several factors. The possible shape could be between a rigid (bottle, jar, can, cap, tray, and tank), a flexible (bag, foamy trays, shrink, bubble, cling wrap, squeezable tube, stand-up packet, and vacuum bag), and a semiflexible packaging (caps and closure, box, tetrapack, and multimaterial). Packaging must show several functions such as protecting food from oxygen, temperature fluctuation, moisture, light, preserve foods from biological microorganism's attack, physical protection from damage while reporting information about the food product, and its identification. Obviously the chemical-physical properties, mechanical performances, gas barrier behavior, and optical characteristics are the key factors in the choice of the most suitable material.

Among the different materials present in the food market, synthetic plastics packaging coming from petroleum resources are the most used thanks to their several positive features such as low-cost, easily processability, economic starting resources, light weight, flexibility, transparency, impermeability, easy of sterilization, and so on. The most common synthetic polymers used for food packaging application are the well-known polyolefins

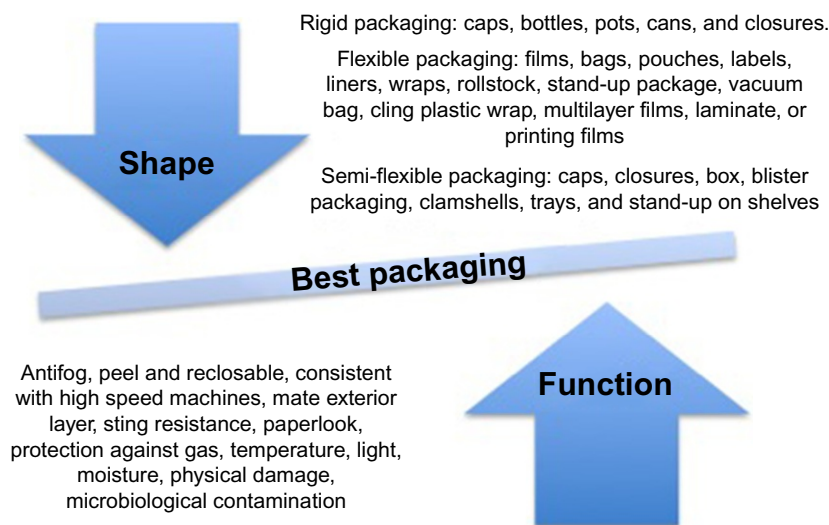


Fig. 1 Balance between shapes and functions of packaging materials.

such as high-density polyethylene, low-density polyethylene, and polypropylene, the substituted olefins such as polystyrene and oriented polystyrene, polyvinyl alcohol, polyvinylchloride, the polyesters such as polyethylene terephthalate and polyethylene naphthalate, and their copolymers, the ethylene polymers such as ethylene vinyl alcohol, ethylene vinyl acetate, and polyamides such as nylon and aramids.

As reported from [PlasticsEurope \(2016\)](#), the main market sector for plastic materials demand is related to packaging ([Fig. 2](#)):

Considering that petroleum-based polymers are not degradable and not eco-friendly, bio-based plastic materials are gaining even more attention as a possible food packaging substitute. At a global level, there is a strong interest in developing new sustainable packaging solutions with the principal focus being in reducing wastes while assessing the environmental impact associated with its production, use, and final disposal.

3 Bio-Based and Biodegradable Food Packaging Materials

According to the definition of European Bioplastics, polymers obtained from renewable resources could be classified into three categories, depending on the origin of the raw materials and on the method of production ([Siracusa, 2016](#); [Robertson, 2013a](#)):

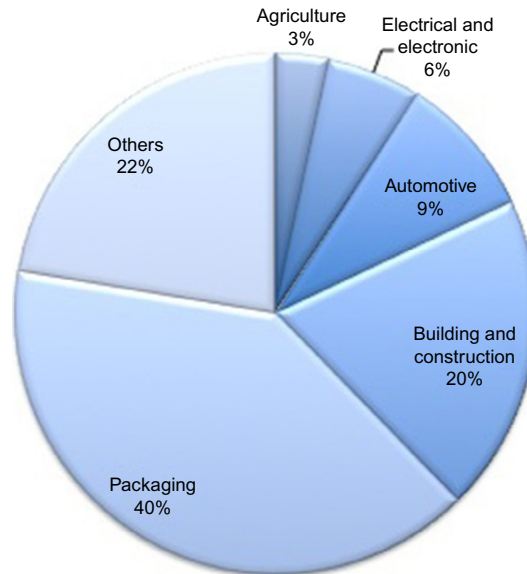


Fig. 2 Main sectors of plastics materials demand. Data from www.plasticeurope.org.

1. Polymers extracted directly from biomass such as polysaccharides obtained from starches of potatoes, rice, corn, maize, and wheat, from hemicelluloses of barley, from gums of guar, alginate, carrageenan and pectin, and from chitosan and chitin, and polymers extracted from animal proteins (such as casein, whey, collagen, and casein) and from plant proteins (such as zein, soy, and gluten).
2. Polymers obtained from monomers synthesized from renewable resources (named bioderived monomers) such as polylactic acid, bio-polyethylene terephthalate, and bio-polyolefins such as bio-polyethylene.
3. Polymer obtained directly from microorganisms such as the family of polyhydroxyalkanoates such as polyhydroxybutyrate, polyhydroxyvalerate, and polyhydroxybutyrate-*co*-valerate copolymers.

In this classification could be also included biodegradable materials obtained from monomers coming from petroleum resources such as polybutylene adipate and its copolymers with polyethylene terephthalate, polybutylene succinate and its copolymers with polybutylene adipate, polycaprolactone, polyglycolic acid, and polypropylene carbonate; that could be considered as the fourth category. It must be kept in mind that biodegradability depends on the final chemical composition of the polymer chain

and not on the origin of the raw material. Consequently a biodegradable polymer could be obtained from monomer coming from renewable or petrochemical resources.

The biodegradation of plastics depends on the chemical structure of the polymers or copolymers, as well as on their crystallinity and molecular weight, and of environmental factors such as temperature, oxygen, moisture, sunlight, and so on. In general, bio-based polymers contain ester, amide, or carbonate hydrolyzable groups in the polymer backbone, which are susceptible to the degradation process by the action of natural microorganisms, converting the material into water, carbon dioxide and biomass (Siracusa et al., 2008).

As reported from European Bioplastics (2013) the worldwide capacity of bio-based plastics is expected to increase from 1.4 Mt (2012) to above 6 Mt (2017). The most important products in terms of production volumes were bio-polyethylene terephthalate (about 39% of global production), followed by bio-polyethylene, polylactic acid, and other biodegradable polyesters (each category sharing 13%–14% of the total market) (Fig. 3).

3.1 Polymers From Biomass

These materials, coming from marine and agriculture resources, are characterized by a high crystallinity and strong intermolecular interaction. Therefore, a right combination of temperature, mechanical shear, and additives such as plasticizers is necessary to avoid degradation phenomena during the thermo-plasticization process.

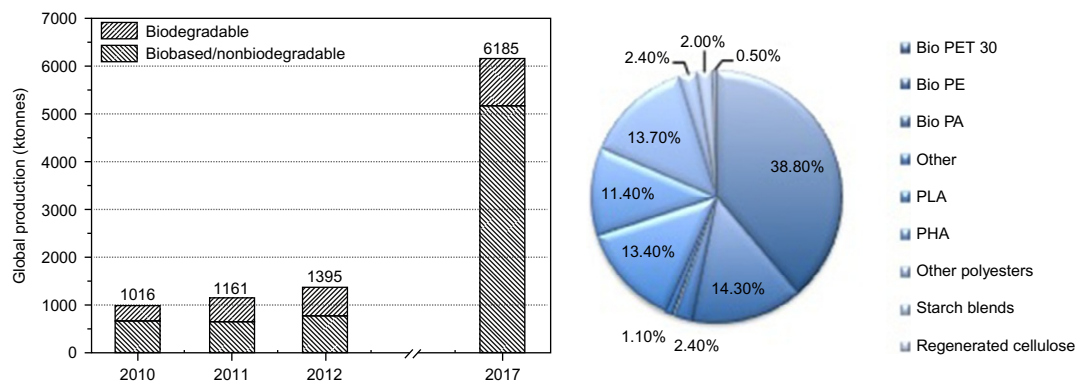


Fig. 3 Global production capacities of bioplastics (European Bioplastics, 2013) by material type. Data from www.plasticeurope.org.

The most used materials are those based on *starch* extracts from cereals such as wheat, corn, rice, and tubers like potatoes. To be used as packaging materials, starch products must be converted into thermoplastic starch materials (TPS). In this case, as the petroleum thermoplastic polymers, TPS can be extruded, injection molded, and blow molded at a temperature between 90°C and 180°C, under shear and in the presence of plasticizers. But, due to the large time required for the stabilization of its properties (several weeks), to the high sensitivity to water vapor and to the low mechanical performance, TPS are unsuitable for several applications. To improve their performance several approaches have been used. The blending with biodegradable petroleum-based polymers such as polycaprolactone, polybutylene adipate-*co*-terephthalate and polyvinyl alcohol improves their processability as well as their biodegradability, giving rise to acceptable barrier and mechanical properties and relative water resistance. The decrease of the water sensitivity was achieved by the chemical modification of the starch polymer chain, after the introduction of less hydrophilic acetate groups.

Cellulose films, obtained by chemically replacing the hydroxyl group with other functional groups, are used for packaging application. Cellulose is biodegradable but not a bio-based material because, being derived from trees, it does not meet the definition of a sustainable material. The commercial name of cellulose film is cellophane, which is a regenerated cellulose film (RCF). In the past, it was substituted by biaxially oriented polypropylene film but, due to the growing interest versus sustainable packaging, it is becoming again popular. RCF is not a plastic material because it cannot be hot pressed and melted. To be used as packaging materials it must be chemically modified or treated with different type of coating. Nitrocellulose is the most common film utilized to provide moisture barrier properties but also it could be used in combination with a polymer coating. Polyvinyl chloride-*co*-vinyl acetate coating is used to obtain a medium film barrier to water vapor, gases, and aromas, approved also for an oven and microwaves use up to 200°C. Polyvinylidene chloride coating is used as moisture barrier material and it could be also metallized. Low-density polyethylene coating is used for high O₂ permeability films for fresh meat packaging application. If three hydroxyl groups of the cellulose are replaced by acetate ones, the cellulose acetate is obtained, which can be formed as films, semirigid containers, and thermoformed blisters. Cellulose acetate is used for fresh fruits and vegetables because it has a high rate of water vapor and gas transmission. In recent years increasing interest was generated on the use of micro and nanofibrils of cellulose

(MCF and NCF) for packaging application due to the fact that used in composite materials or in coatings and films they impart positive performance such as improved gas barrier properties, mechanical properties, and biodegradability (Spence et al., 2011; Sirò & Plackett, 2010). There is also a growing interest on *hemicellulose* (Hansen & Plackett, 2008) as bio-based food packaging materials, obtained from hard wood and barely but until now they are not present into the market.

Chitin and chitosan are two of the most studied chemical substances used to produce edible films and coatings with antimicrobial activity, for fresh fruits and vegetables. They present poor mechanical and water resistance. Polymers coming from proteins have not yet used as food packaging materials due to the difficulty in their processing, low thermal stability, incompatibility to the most polymers and high costs. They are very interesting as bio-based materials owing to their inherent biodegradability so their future application could be their application as edible films. The most commercialized protein packaging materials are that obtained from collagen sausage casings while the most recent biodegradable thermoplastics is obtained from methyl acrylate graft polymerization of chicken feather, rich in β -keratins. Feather films obtained showed higher tensile properties than other soy protein and starch acetate bio-based films (Jin et al., 2011).

3.2 Polymers From Renewable Resource

Today, both academic and industrial researches are oriented versus bio-based alternatives to petroleum derivative materials, with enhanced properties for several applications such as the food's packaging field. The number of companies producing, processing, or using biomaterials is considerably expanding. As reported in Fig. 4, bioplastics are already employed in many different fields, ranging from rigid and flexible packaging to agriculture, from medicine and pharmacology to building and automotive.

The use of renewable resources is growing but, the obtained polymers, present several problems compared with the synthetic ones. In particular, they cannot be processed with traditional technologies and their functional and structural properties present less performance (Mensitieri et al., 2011). By tailoring their chemical-physical properties they become adaptable to specific processing and structural demands. For this purpose, additives such as stabilizers, plasticizers, antioxidant, fillers, and so on have to be added during the polymerization process. Further, blends, composites, and laminates between synthetic polymers and

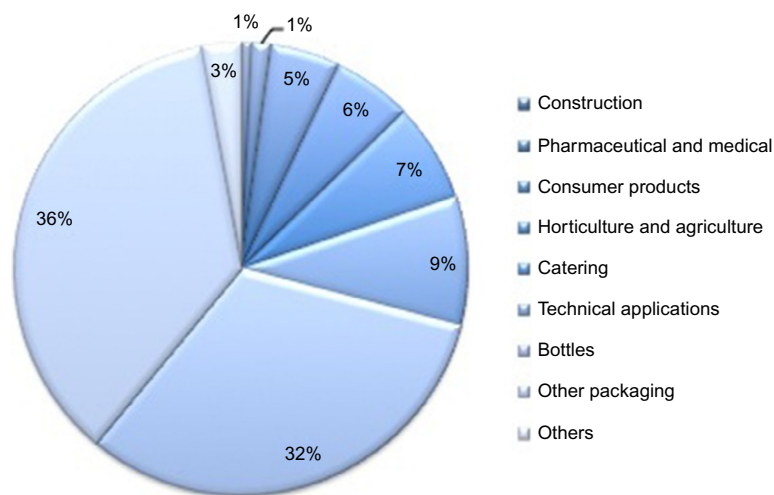


Fig. 4 Plastic materials demand of bioplastics in 2012 by market segments. Data from www.plasticeurope.org.

polymers obtained from renewable resources, have been studied, with the aim to expand the range of application (Siracusa et al., 2008; Mahalik & Nambiar, 2010).

Between all the bio-polyesters produced and present into the market, polylactic acid is the most commercialized one owing to its potential if compared with the synthetic polymers coming from petroleum (Auras et al., 2010). Polylactic acid is a linear aliphatic polyester that could be synthesized from lactic acid monomers obtained from the fermentation of glucose extract from starch in biomass (corn and wheat), from lactose in whey and from sucrose in molasses (Siracusa et al., 2012; Siracusa & Ingraio, 2016). The monomer could be also obtained by petrochemical route. Lactide monomer is a mix of L(+), D(−) and meso-lactide stereoisomers. The synthesis could be achieved by direct condensation or by ring-opening polymerization (ROP). The first approach, being an equilibrium reaction, gives rise to a low molecular weight polymer, due to the difficulty in removing the water during the last stage of polymerization where the molecular weight increases. The second approach, ROP, is a solvent free process, catalyzed by tin and zinc oxides or chlorides or by stannous-2-ethylhexanoate. The properties of polylactic acid, as well as the final molecular weight value, vary according to the ratio and distribution of the isomers. While the poly(L-lactide) and the poly(D-lactide) are semicrystalline polymers, the atactic polymer poly(D,L-lactide) is amorphous. The ratio between the

crystalline and amorphous phase is determinant for the corresponding appearance of the polymer. The amorphous phase gives up a clear material while the crystalline phase of an opaque and white material. The corresponding transition temperature (T_g) and melting temperature (T_m) are important for commercial application of polylactic acid. The polymer is rigid due to the high- T_g value (50–60°C) but by the use of plasticizers additives the T_g could be lowered giving rise to polymer with a lower stress at yield and higher elongation at break, at room temperature (Siracusa & Ingraio, 2016). Polylactic acid is biodegradable at temperatures above the T_g and compostable in industrial composters.

Bio-polyethylene and bio-polyethylene terephthalate are two of the emerging polymers obtained from renewable resources. They are not biodegradable but they have the same properties, processing, and performance as polyethylene and polyethylene terephthalate made from natural gas or oil feedstocks. Bio-ethylene is produced starting from bioethanol obtained from the fermentation of sugarcane, sugar beet, and wheat grain. Bioethanol from sugarcane is produced mainly from Braskem with Toyota Tsusho Corporation and from Dow Chemical Company with Crystalsev. Recently, bio-propylene has produced bio-polypropylene (Robertson, 2013a).

For the production of bio-polyethylene terephthalate, the bio-ethylene glycol coming from sugarcane was used. The first product was commercialized from The Coca-Cola Company with the trade name of PlanBottle, where a 30% of bio-ethylene glycol was used by weight for the production of polyethylene terephthalate. To obtain a 100% bio-based materials the researchers are working on the synthesis of bio-terephthalic acid. PepsiCo also announced the use of a polyethylene terephthalate bottle made entirely with renewable resources coming from waste carbohydrate biomass obtained from the food industry such as orange peels, oat hulls, corn husks, and potato scraps.

Avantium company is developing a new 100% bio-based polyester with the same structure as polyethylene terephthalate obtained from bio-ethylene glycol and bio-terephthalic acid but also replacing the terephthalic acid by 2,5-furandicarboxylic acid, coming from the dehydration of carbohydrates, to produce the polyethylene furanoate (Smith, 2015). Polyethylene terephthalate is one of the most studied polymers to be transformed in commercial bio-based plastics. The interest gives life to a Technological Collaboration between Coca-Cola, Ford, Heinz, Nike, and Proctor & Gamble, with retailers and enterprises such as Avantium and Micromidas, to develop commercial processes for the production of bio-based polyethylene terephthalate and polyethylene furanoate.

3.3 Polymers From Microorganisms

This kind of polymers, obtained from microorganisms belong to the family of polyhydroxy alkanoates (Peelman et al., 2015). They came from renewable resources such as sugars and are biodegradable and biocompatible linear polyesters. In anaerobic environment, the degradation products are carbon dioxide and methane gases. The most common is the polyhydroxybutyrate, the polyhydroxyvalerate and their copolymers Polyhydroxybutyrate-*co*-valerate. The ratio between hydroxybutyric and hydroxyvalerate determines the final mechanical and physical properties such as flexibility, tensile strength, and melting point. If a high percentage of hydroxybutyrate is present, the copolymer is similar to polypropylene while if a high percentage of hydroxyvalerate is used, the corresponding polymer is similar to high-density polyethylene. Polyhydroxybutyrate-*co*-valerate copolymers have a good oxygen and aroma barrier behavior, good chemical and moisture performance. The mechanical behavior could be improved by copolymerization with other polymers and by inorganic materials. Thanks to the innovation in the production technologies, the price is lowering, becoming even closer to that of other biodegradable polymers such as polylactic acid. The most expensive phase is the carbon substrate production but researchers are currently working on low-cost substrates such as whey, wastewaters from olive mills, molasses, corn steep liquor, starchy wastewaters, and palm oil effluents (Koller et al., 2010). Bacterial synthesis is very expensive too, so genetically modified crops are taken into consideration for the production of polyhydroxyalkanoate that could be extracted from plant materials. This procedure is more difficult than those from microorganisms so this technology is still in progress.

An emerging technology is associated with the production of polymer films for food packaging industry from bacterial cellulose (BC). The corresponding polymers have a very low permeability to gases in the dry state but the permeability drastically changes if in wet ambient. To improve the barrier properties a chemical modification could be performed, such as acetylation, nitration, amination, and hexanoylation. Until present they are not commercialized and are studied only on a lab scale. They are also used as bio-reinforcement in nanocomposites.

3.4 Polymer From Petrochemical Resources but Biodegradable

In this category are included polymers coming from monomers obtained from nonrenewable petroleum resources, can be aliphatic polyesters or aliphatic-aromatic copolyesters and are

biodegradable. Between them, the most common and commercial available are the Polycaprolactone, polybutylene adipate-*co*-terephthalate, polybutylene succinate and its copolymers, polyglycolic acid and polypropylene carbonate. Polycaprolactone is obtained by ROP of ϵ -caprolactone, which is obtained from the oxidation of cyclohexanone. Owing to its high cost it is not used for large-scale packaging application. The most commercialized one is under the trade name of Mater-Bi from Novamont where, to increase the biodegradability and lower the cost, it is mixed with starch. Starch-polycaprolactone copolymers with up to 20% of polycaprolactone content show good oxygen barrier behavior but by increasing the content of the gas barrier properties deteriorate while the water vapor barrier improves.

Polybutylene adipate-*co*-terephthalate is obtained by polycondensation of 1,4-butanediol, Adipic acid and Terephthalic acid. It is an aliphatic-aromatic copolyester with mechanical performance similar to those of polyethylene. The commercial name is Ecoflex, commercialized by BASF, and used as food packaging material for fresh meats, fruits, and vegetables. It could be blended with other biodegradable polymers such as polylactic acid or starch to tailor the physical-chemical, mechanical and barrier properties (Wang et al., 2016).

Polybutylene succinate and poly(butylene succinate-*co*-adipate) are obtained by polycondensation of succinic acid (or dimethyl succinate) or adipic acid with ethylene glycol or 1,4-butanediol. The monomer could be obtained from both renewable and nonrenewable resources. The trade name is Bionolle and is commercialized from Showa Highpolymer. Thanks to their excellent processability using conventional equipment they can be injected, extruded, and blown. When terephthalic acid is used the corresponding polybutylene succinate-*co*-terephthalate is obtained while if succinic acid and 1,3-propanediol is used instead of ethylene glycol or 1,4-butanediol, the poly(butylene succinate-*co*-propylene succinate) is obtained. Recently a bio-1,3-propanediol was obtained from aerobic fermentation of corn glucose to synthesize the poly(butylene succinate-*co*-propylene succinate) copolyester (Liu et al., 2010).

Polyglycolic acid is obtained by polycondensation or ROP of glycolic acid. It is an interesting biodegradable thermoplastic aliphatic polyester, with superior barrier performances to both oxygen and carbon dioxide and excellent mechanical properties. It is employed in multilayer bottles with polyethylene terephthalate, for carbonated drinks. In combination with polylactic acid it was observed an enhancement of the biodegradable properties such as the barrier behavior. The trade name is Kuredux,

commercialized in the United States, is certified as biodegradable material, with a rate of biodegradation similar to that of cellulose (1 month in compost) releasing water and carbon dioxide.

Polypropylene carbonate is an aliphatic polymer containing C—O—C bonds and C=O groups. It is a hydrophobic, amorphous polymer, with low T_g and thermal stability. To improve its mechanical and thermal properties, it is used for blending with other polymers. In this case biodegradable polymers such as polylactic acid, polybutylene succinate, poly(butylene adipate-co-terephthalate) and starch or nanoparticles such as montmorillonites could be used.

4 Edible Food Packaging Materials

The functions of edible packaging materials are very similar to those of synthetic and not edible ones. They have to be selective as barrier materials to control and limit the migration of moisture, gases, oil, fat, volatile flavor compounds and aromas from food, they have to enhance the nutritional and organoleptic properties of packed food while improving or at least maintaining the mechanical performance. But, the most important feature is their resistance to the migration of water vapor to preserve the food deterioration. Due to the fact that these materials have a biodegradable nature, which is the most important benefit, there is a strong limitation on their use. In fact, they cannot replace the traditional packaging materials but they are used to improve the overall food quality to extend the shelf life of packed foods. As reported from [Gennadios \(2002\)](#), they present several positive features. They can be eaten together with the food because they are made with edible ingredient, they are useful to add elements such as flavor, colour, and sweet taste to the food, they can be used to add additional food nutriment such as proteins and, further, they can act as carrier for antioxidant and antimicrobial agents and as controller for the diffusion of preservatives from the surface to the inside of the packed food.

Edible packaging materials could be in the form of edible films, sheets, pouches, and coatings. While the first three types are stand-alone structure that could be placed on food or sealed into pouches, edible coatings are formed directly on the food surface as very thin layers ([Falguera et al., 2011a,b](#)).

To obtain the best edible materials several chemical parameters have to be controlled. First of all, the molecular weight of the polymer is very important, that must be high enough for a self-standing film. To improve the cohesion between film and

food, long chain polymers with high polarity are required to increase the number of hydrogen bonds and ionic interactions.

Further, to enhance the properties of such edible bio-based materials, several additives are incorporated in the formulation. First of all plasticizers additives, such as saccharides (glucose, fructose, and sucrose), glyceryl derivatives (glycerol, sorbitol, and polyethylene glycols) and lipids derivatives, added to improve the film flexibility and strength. Emulsifiers additives, used to improve the films surface wettability and lipid dispersion. Antimicrobials additives, used to increase and prolong the shelf life of packed foods. In this case, much attention has to be given on the choice of the best agent because their interaction with biopolymer materials and the processing condition could alter their functionality. These additives could be used also to improve the nutritional value of food when used as carriers of substances. The most common are organic acids, chitosan, nisin, and essential oils (Sirocchi et al., 2017). It must be taken in mind that these agents are not a substitute for correct food manufacturing, but they are adjuvant for improving the overall food quality. Antioxidant additives are used on edible films to inhibit or delay the food oxidation process. They can act as oxygen scavengers, oxygen deactivation, and UV absorbing radiation or as a promoter of antioxidant activity of the antioxidant incorporated into the films. Citric and ascorbic acid, tartaric acid, herbs such as rosemary, sage, thyme, tea, and oregano are the most used. These additives are gaining even more attention by the researchers as well as from the industry as substitute on synthetic preservatives to achieve a more sustainable films formulation. Already carried out in the United States, the future could be the commercialization, of edible films obtained from fruits and vegetables (Martin-Belloso et al., 2009) such as broccoli, carrot, tomato, mango, apple, banana, peach, and pear.

One of the main problems of an edible coating for minimally processed fruits and vegetables is that the food surface is wet and remains like this for a long time. As a result there is a very low adherence of those films on the food surface with a consequent loss in efficacy. One possibility is to obtain dry films as for example by infrared drying technic (Martin-Belloso et al., 2009).

Several polysaccharides, proteins, and lipid coming from plants and animals could be used alone or in mixture to obtain the desired materials (Robertson, 2013a). In recent study, the tendency to produce edible films by combining various elements such as polysaccharides, proteins and lipids was expressed with the aim of taking advantage of the properties of each component.

Obviously, the final performance, such as mechanical and barrier behavior as well as transparency for consumer's acceptability, will depend on the compatibility and type used in the polymer matrix. The choice of the best edible film composition is one of the most important fields of research because it must be formulated according to the properties of fruits and vegetables to which it has to be applied, during the storage time (Rojas-Grau et al., 2009). Thereby, microbiological stability, adhesion, cohesion, wettability, solubility, transparency, mechanical, and permeability behavior to water vapor and gases, could be tailored and adapted to the final application by the optimization of their composition.

4.1 Polysaccharides Edible Films

Polysaccharide edible films are the most commercialized ones owing to their good mechanical performance, good gas barrier behavior and oils and lipids barrier, low-cost, being easy to handle and process. Due to their intrinsic nature, they are susceptible to humidity and low water resistant, which make them biodegradable materials.

Starch, a mixture of amylose and amylopectin, is the major compound studied. To improve water solubility, the esterification of amylose with propylene oxide, to give the corresponding hydroxypropylated materials, is used. They are mainly used for bakery, confectionary (such as chocolate), batters, and meat (Janjarasskul & Krochta, 2010). From the hydrolysis of starch a low molecular weight carbohydrate, named dextrin, is obtained and used as an edible coating, glue, and sealant.

Cellulose is the most abundant primary material. Before to be processed for packaging application, it must be chemically modified by substitution of the numerous hydroxyl functions with acetate or methyl groups. As a result, the reduction of the physical network and the decrease of the number of hydrogen bonds make it easier to process and be transformed into films. Being dependent on the chemical modification several types of cellulose materials could be obtained, with tailored properties such as solubility, mechanical properties, and oxygen and lipid barrier behavior. The most common are methylcellulose, hydroxypropyl cellulose, hydroxypropyl methylcellulose and carboxymethyl cellulose, with good film-making properties (Robertson, 2013a).

Hemicelluloses, polysaccharides coming from sugars such as glucose, xylose, mannose, galactose, rhamnose, and arabinose extract from barley, oats, corns, and maize brans are principally used as edible coatings.

Chitin, present in the exoskeleton of arthropods and in the cell walls of insects, which is an acetylated polysaccharides and *chitosan*, obtained by deacetylation with alkalis of the chitin, are non-toxic polysaccharides approved to be used as food additives and as coating materials. Their properties depend on their molecular weight and on the degree of acetylation. Aider (2010) described well the characteristics of these materials and their potential application in the field of food packaging, particularly owing to their antimicrobial properties while Tamer and Çopur (2010) described the use of chitosan as edible coating for fresh-cut fruit and vegetables could increase the food shelf life while reducing the microbial activity.

Alginate coatings obtained from brown seaweeds are used to protect food against oxidation owing to their good oxygen barrier properties. *Carrageenan films* and *Agar films*, obtained from red seaweeds, is used thanks to its properties to reduce moisture loss, oxidation and as carrier of antimicrobials for meat food.

Pectin coatings are used as retardant of water loss from food because when moisture evaporates they act as a sacrificial material. They also retard the lipid migration from food enhancing the appearance and handling of foods. Cagri et al. (2004) in their paper on edible films and coatings reviewed the various types of polysaccharide-based (cellulose, chitosan, alginate, starch, pectin, and dextrin), edible films that can be used as films to enhance the safety and shelf life of ready-to-eat foods.

4.2 Proteins Edible Films

Several proteins, proposed for the production of thermoplastic polymers, could be available as by-product from agricultural activities but also from biofuel processing for the production of bioethanol (Falguera et al., 2011a,b; Cuq et al., 1998).

Protein edible films and coatings are obtained from proteins coming from animals and plants such as collagen and gelatin, wheat gluten, corn zein, soy, rice, pea and whey protein, casein, egg white, fish, and so on. They present good flexibility due to the presence of large amount of hydrophilic substances such as glycerin and sorbitol. Naturally, they show good mechanical properties, optical performance, and barrier behavior against oxygen, carbon dioxide, and aroma. Due to their inherent hydrophilicity, and consequently good biodegradability, their mechanical performance and water vapor permeability could be compromised by changes in environmental moisture content. Those properties could be improved by chemical or physical cross-linking.

Collagen films are used for reducing beef exudation when defrosted to avoid colour depletion or lipid oxidation. When used for cooked meat they reduce shrink loss, absorbing exudate and increase juiciness.

Gelatin films are used for encapsulating oil-based and low moisture food ingredients owing to their ability in reducing oxygen and water vapor permeability and oil migration.

Milk protein edible films and coatings present reduced oxygen permeability, very important to avoid rancidity and lipid oxidation in fat food such as roasted peanuts, salmon, peanuts butter, mayonnaise, and chicken breasts.

Cereal protein edible films coming from zein, with high performance as barrier materials against oxygen, moisture and lipid, are used commercially for confectionery product such as candies, chocolate, and so on. As reported by [Lia and Padua \(1999\)](#), it is a better moisture barrier material than other protein material such as casein or polysaccharides such as starch, owing to its high content of nonpolar amino acid groups, with its hydrophobic behavior.

4.3 Lipids Edible Films

Since these materials have a low molecular weight and are not polymers, they cannot be used as films with defined characteristics. Thanks to their low polarity they are used as moisture barrier material. Wax from natural products such as carnauba, rice bran, bees, synthetic wax such as paraffin and mineral, and vegetable oils have been used to protect fresh fruits and vegetables. Despite the fact that they are used to protect the food surface, they can confer a waxy or a rancid taste to the food. Further, transparency could be affected as well as mechanical performance of the final polymer matrix. To overcome the poor mechanical strength, lipid compound can be used in combination with hydrophilic materials, forming an emulsion compound, or with a hydrocolloid film lipid layer by lamination. But, despite emulsion films are less efficient than laminated films due to the fact that lipids are not homogeneously dispersed, they have good mechanical performance and require simple processes for their manufacture and application. The smaller are the lipid particle size, the more homogeneously are distributed, with lower water vapor permeability ([Falguera et al., 2011a,b](#); [Cagri et al., 2004](#)). Multilayer films are difficult to processes, depending also on the number of coatings. Shellac edible coating was used for confectionary and fresh products ([Baldwin, 2007](#)).

5 Bio-Composites Materials

To improve the mechanical and barrier properties of bio-based materials to make them competitive with petrochemical-based polymers, the most used tool is to mix them with nanoparticles, obtaining the corresponding bio-nanocomposites materials. In this case, inorganic and organic fillers with particular chemical functionalities, geometry and size are mixed with biopolymers, enhancing their properties and lowering their price (Sorrentino et al., 2007; Chivrac et al., 2009). The most affected properties are the mechanical, thermal, and gases permeability. In this case, it is very important to obtain a uniform dispersion of the nanofillers to assure a great polymer matrix versus nanofiller interfacial area and higher reinforcing effects. The most used nanocomposites for bio-based polymers are nanoclays and polysaccharides for polylactic acid, polycaprolactone, polybutylene succinate, poly(butylene adipate-*co*-terephthalate), polypropylene carbonate, poly(hydroxybutyrate-*co*-valerate), and polyvinyl alcohol (Tang et al., 2008). Gordon in its book described the use of such chemical on bio-based polymers, reporting the corresponding improvement on the chemical-physical, mechanical, and gas barrier properties (Robertson, 2013a). Several parameters have to be controlled to achieve the best affinity between the polymer and fillers. The most promising reinforcing materials are nanobiofillers such as cellulose nanowhiskers with large surface-to-mass ratio, high mechanical strength, flexibility, lightness, and also edibility, considering that they are obtained from hydrocolloids (Lagaron & Lopez-Rubio, 2011). A future application in the field of food packaging is not excluded (Azeredo et al., 2009; De Moura et al., 2009). Further, nanoparticles can be used as a carrier for antimicrobials and antioxidant additives, for increasing stability during storage, for reducing food spoilage, for maintain flavor, aroma, colour, texture, and so on.

6 Performances and Packaging Applications

The most important properties of bio-based materials for food packaging applications are the barrier and mechanical properties. Regarding the barrier properties, biopolymers show several problems, especially in high moisture condition. To improve such behavior one possible route is to coat them with synthetic polymers, limiting drastically their use as bio-based materials. It must be underlined that in literature several information are present

about the water vapor transmission rate (WVTR) and gas transmission rate (GTR) but these information lack in precision due to the fact that most of the time data on sample thickness, temperature, and humidity at which measurements were made and variation in test methodology, crystallinity, amorphous content, and films preparation are missing. Therefore data reported in literature have to be used with caution for food packaging application. As an example, [Siracusa and Ingraio \(2017\)](#) reported a full gas barrier behavior study performed on several biaxially oriented polypropylene films, of different thickness, at different temperature, used for food packaging application. In this case, the influence of both temperature and thickness on the final polymer performances was reported and fully described. The same research could be performed on bioplastics materials because it was demonstrated that it is not always easy to compare data present in the literature with the experimental ones. The variation of data is correlated to several factors such as thickness, molecular weight, density, crystallinity/amorphous phase percentage of polymer matrix, and so on. Also, slight change in polymer formulation due to change in process conditions, should not be overlooked to not over or lower estimate the packaging performance requested to extend the food shelf life.

Between all the biopolymers, polylactic acid, and polyhydroxyalkanoates are the two materials with the lower dependence to the ambient humidity ([Auras et al., 2004, 2006](#); [Almenar & Auras, 2010](#); [Bao et al, 2006](#); [Thellen et al., 2008](#)). Polylactic acid has a WVTR three to five times higher than the commercial polymers such as polyethylene terephthalate, high-density polyethylene, low-density polyethylene, and oriented polystyrene, while polyhydroxy alkanoates have a WVTR very similar to those of petrochemical ones. Polylactic acid has better O₂-TR properties than polystyrene but not as polyethylene terephthalate while polyhydroxybutyrate is better than polyethylene terephthalate and polypropylene with good fat and aroma barrier properties for food with short shelf life. To improve the barrier properties several techniques were proposed such as mono- or biaxially orientation, coating with organic layer such as SiO₂, metallization, blending with nanofillers for nanocomposites preparation ([Cushen et al., 2012](#)).

The most important parameters influencing the mechanical performance are the molecular weight, the chain backbone architecture such as the presence of linear and/or branched polymer chains, the ratio between the crystalline phase and the amorphous phase. Mono- or bi-orientation of the polymer chains improves the mechanical strength as well as the heat stability.

Change in crystallinity and molecular weight could allow to changes between soft and elastic to stiff and strength material. The most studied material was the polylactic acid, the most commercialized biomaterial. Plasticizers such as water, polyols, polyethylene glycol, and citrates were used to pass from a brittle to a ductile behavior for polylactic acid polymers, to produce a flexible films (Vieira et al., 2011; Cairncross et al., 2005; Almenar & Auras, 2010; Holm et al., 2006). McCarty et al. (1999) is the author of a patent describing the results obtained when PLA was blended with 20% of any biodegradable aliphatic copolyesters such as polycaprolactone, Ecoflex, Bionolle and polyhydroxyalkanoates. By tailoring the copolymer composition is possible to modulate the corresponding mechanical as well as thermal and barrier properties.

Also the mechanical performance of the polyhydroxyalkanoates can be modulated by changing the molecular structure and the copolymer composition, changing from hard crystalline plastic material to elastic rubber material.

Despite the considerable amount of research and results obtained on the study of bio-based materials, their commercial use is still limited (Gontard et al., 2011). At present, they are used for short shelf life food stored at chill temperature and dry ambient, due to their inherent biodegradability, which is manifested especially in moisture ambient. Potential application could be for fresh fruit and vegetable minimally processed, due to the high CO₂/O₂ permeability ratio, useful for respiring food. For moist food there are some limitation due to their sensitivity for humidity and consequently low water vapor barrier property. Polylactic acid remains still the most utilized biopolymer for food packaging application. Several results were published regarding its use for fresh salmon packaging (Pettersen et al., 2011) in the form of oriented polylactic acid and for blackberries packaging (Joo et al., 2011), comparing its performance with synthetic polymers such as polyethylene terephthalate, low-density polyethylene and oriented polystyrene.

Edible films and coatings are studied by researchers as possible tools for the reduction in fried food products, as means for active compounds migration and shelf life extension of high perishable foods such as fresh-cut fruits and vegetables and for meats and fishes. Consumers, more conscious in their health, are driving the interest to the reduction of oil incorporation during frying process (Freitas et al., 2009). Consumers are more interest for fresh and minimally processed food, enriched with natural substances and not with chemical substances, while maintaining their nutritional and sensory characteristics (Falguera et al., 2011a,b).

Considering that taste and flavor must be maintained during food storage, the encapsulation of aromatic compounds such as ethyl acetate, ethyl butyrate, ethyl octanoate, 2-pentanone, and so on ([Marcuzzo et al., 2010](#)) could be used as a strategy to reduce degradation reactions such as oxidation. Lastly, various active compounds such as antioxidants, flavorings, antibrowning, antimicrobials, vitamins, and enzymes, as transport and release means, are the future of edible films and coatings, while nanotechnology is an emerging technology that could be used to release, in a controlled manner, the encapsulated bioactive compounds from the matrix to the product ([Rojas-Grau et al., 2009](#)). The main limitation on the commercial use of edible films and coating are the problems related to the poor mechanical and barrier properties. Improving their performance by adding reinforcing nanocompound is not always possible due to safety concerns. While the properties of macromolecules are well-known about their eventual toxicological effects, scientific data about the effect of nanostructures for human health must be still followed, for any future commercialization. The positive feature is that edible films and coatings fit several environmental parameters suggested by US Environmental Protection Agency (EPA) ([Dangaran et al., 2009](#)) like:

- to be “green packaging,” because they improve municipal waste management and waste reduction,
- to reduce the amount of toxic materials in packaging, making easier the reuse or composting them,
- to reduce the amount of food wastes owing to the reduction of damage and/or spoilage on food products.

7 Food Packaging Sustainability

According to [Marsh and Bugusu \(2007\)](#), food packaging is one of the principal causes of waste productions in fact it is ~50% of the total packages sold, being the two-third of total packaging waste by volume. The result is that the assessment and reduction of the environmental impact associated with the production, use and final-end of these materials are one of the most important priorities of the food packaging industries. Further, different life cycle phases associated to food packaging, such as production, transport, use, solid waste disposal, and so on causes different environmental impacts, correlated also to the consumption of nonrenewable and renewable resources such as materials and energies, air, and water emissions ([James et al., 2005](#)).

The massive consumption of plastics packaging materials is related to different causes (Verghese, 2008). The first is that, according to the change in human nutrition and life habits, the request of small package size is increasing, giving a great contribution to the increase of plastics wastes. Secondary, a difficulty in the recycling process due to the use of different packaging materials requested by industry and by consumers to satisfy economic, health, quality and new cooking styles needs, is increasing even more the production of solid wastes.

To take into consideration the growing environmental concern, packaging industries are working on reducing the weight and volume of packaging eliminating the unnecessary component, while assuring the correct shelf life, safety, and protection functions of the packaging. Further, improvement of the recyclability, reusability, composting, and energy recovery are other tools considered by industries to reduce wastes production. Using new materials such as biopolymers and improving the product shelf life could give a great contribution for sustainable development due to the fact that the longer the shelf life is, the lower food and packaging wastes are (Restuccia et al., 2016). The world's largest retailer, the US WalMart Store, is a leader on sustainable initiatives such as the promotion of the Packaging Scorecard, which is a tool introduced to evaluate the performance and the efforts of the suppliers to work on and select the best packaging with reduced environmental impacts (Robertson, 2013b). Further, the European Organization for Packaging and the Environment (European) support that is better to talk about packaging and sustainability rather than sustainable packaging. They consider packaging not as a problem but as part of the environmental solution for a sustainable development. From this point of view a packaging gives a considerable contribution to economic, environmental and social sustainability because it protects the food products while reducing wastes (food and material wastes). Following the European's vision (European, 2009), to minimize the impacts and maximize the benefits, for a sustainable development a packaging should:

- be designed holistically with the product to optimize overall environmental performance
- be made from responsibility sourced materials
- be designed to be effective and safe throughout its life cycle
- meet market criteria for performance and cost
- meet consumer choice and expectations
- be recovered efficiently after use.

A packaging material impact not only during its production and disposal but also during the packing, in the food chain, and

its distribution. Johnson in his work (Johnson, 2009) discussed the eight criteria reported from the US-based Sustainable Packaging Coalition (SPC) (SPC, 2011) for identifying what a sustainable packaging material must display. In particular:

- it must be beneficial, safe, and healthy for individuals and communities throughout its life cycle;
- it should meet market criteria for performance and cost;
- it must be sourced, manufactured, transported, and recycled using renewable energy;
- it optimizes the use of renewable or recycled source materials;
- it must be manufactured using clean production technologies and best practices;
- it is made from materials healthy throughout the life cycle;
- it is physically designed to optimize materials and energies;
- it is effectively recovered and utilized in biological and or industrial closed-loop cycle.

It must be taken into consideration that the choice of packaging material could respect one or more criteria but could be contradictory for others. For example, a packaging could be produced using renewable resources but more energy is utilized to produce and transport it than a material produced by a nonrenewable resources.

In 2009, the Consumer Goods Forum (CGF) was created with the aim to connect retailers, manufacturers, service providers, and stakeholders from all over the world to discuss and assess the packaging sustainability. In 2010, they published *A Global Language for Packaging Sustainability* while in 2011, they published the Global Protocol on Packaging Sustainability (GPPS, 2011), giving the possibility to standardize the questions about the packaging sustainability, within a company or between business partners.

7.1 Life Cycle Assessment

To consider all the environmental impacts, a life cycle thinking (LCT) approach is the most used tool, with the definition of the environmental burden of a food packaging. All environmental, social, and economic impacts through the whole life cycle of a product have to be considered. Different LCT tools could be used to perform an environmental study such as life cycle assessment (LCA), life cycle costing (LCC), social LCA, the eco-design, carbon, water, and ecological footprint. Between them, the most utilized and accepted methodology is the LCA for measuring the environmental performance of products and processes. The LCA methodology is useful for the identification and assessment of potential

impacts associated with a material, product, service, and/or process, from raw material extraction and processing to manufacturing, transport, use and final disposal, throughout the entire life cycle (Guinée, 2002). It is applied in accordance with the indication of the International Organization for Standardization (ISO) standards (ISO14040, 2006; ISO14044, 2006). It is usually referred to a “cradle-to-grave” analysis but also a “cradle-to-gate” analysis could be performed. Typically two or more products with the same use are compared. According to ISO standards, a LCA study is divided into four steps:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Life cycle impact analysis (LCIA)
4. Life cycle interpretation

Goal and scope definition. This is the step where the intended motivation for conducting the study is defined. Results, audience, geographical area, functional unit, system boundaries, data, procedure for handling the data, limits, are well identified in this step. The functional unit, that is, the unit of product that will be the object of the LCA study, have to be chosen to avoid losing time and to well compare the results obtained. All input and output data are related to this functional unit. In general, for food packaging application, it is a defined volume of materials such as, for example, 1 kg of polymer. The goal and scope can also be adjusted during the LCA study if the initial choice is not optimal. In this step could be drawing a diagram of the system, starting to identify the boundaries. Also, in this step the model used must be indicated. Is it possible to use a consequential model or an attributional model? The consequential model is used when the scope is to investigate the consequences of a change of a starting situation. The attributional model is used when the environmental impacts assessment of a product, a process or a comparison with two products with the same functional unit is required. All the environmental inputs and outputs data are expressed for the raw materials extraction (from cradle) to the gate of the product or supplier or to the final disposal of the material (grave).

Life cycle inventory (LCI). In this step the data collection is very important and could be classified as primary and secondary ones. Primary data are obtained directly from the original source as for example the food industry. The secondary data are extrapolated from official databases, included in the LCA software, recognized from the research word. The primary data that are necessary to well describe the system under study are called “Foreground data” while the secondary data which are referred to a generic materials, energy, transport, and waste management and that can be found

in databases or literature are called “background data.” Fore-ground data could be collected following the questionnaires described in the ISO standards that contain in a simple way, generic information, and explanation for each data requested, data sections, data quality, and allocation. The use of background data requires much attention because they have to fit with the requirement of the goal and scope of the LCA study. The two most important data sources are the Ecoinvent database and the Input-Output database. The first ones have been created by several Swiss organizations and cover over than 10,000 processes while in the second ones data are collected per economic sector rather than per processes.

The LCI quantifies the use of resources and materials, the consumption of fuels and energies, the involved transportation. All data that cannot be identified and expressed quantitatively are not included in the study. All input and output data are described as a framework. These data are referred to the involved materials and energies used for the production of a product or for a process. Several individual units operations are identified, each well described from several input and output data.

Life cycle impact analysis (LCIA). In this step, all data collected and described during the LCI analysis are converted in several indicators. To do that different method could be used, depending on the audience addressed and on the ability of the audience to understand the results. Each method contains from 10 to 20 impact categories which are grouped in Damage Categories such as Resources, Climate Change, Human Health, Ecosystem Quality, and so on, internationally accepted, scientifically valid, and environmentally relevant. Some of these could be aggregated in single score and some do not. Until now, there is no indication on what the best method is. For each damage category, several impact categories are identified. For example for the damage category Ecosystem Quality the following Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acidification/nitrification, Aquatic acidification, Aquatic eutrophication, Land occupation impact categories are considered. The aim of this phase is to understand and evaluate the magnitude and significance of the environmental impacts.

Life cycle interpretation. In this last step, a conclusion and a solution of the environmental study must be performed. Results obtained from LCI and LCIA phases are combined together to identify the most impacting categories. Opportunities to reduce the environmental impacts of the product system investigated must be given, with the subsequent indication of limitations and recommendations. Results obtained from this last phase

are used for direct applications on product development and improvement, for strategic planning, for marketing, for social policy making, and so on.

7.2 Application of LCA to Food Packaging

A comparison between multilayer and monolayer packaging could be performed. It is obvious that the multilayer material is not an environmentally friendly solution in respect to the single-layer where less material and energy is used. But, if the longer food shelf life is also included in the study, with a multilayer packaging less energy is used during storage and distribution of the packed food and also a minor food waste could be supposed (Lee & Xu, 2005). It can be concluded that a multilayer material could have a less environmental impact.

Biodegradable material or bio-based materials are of course considered as environmental friendly polymers than synthetic ones, but if they are mixed with traditional polymers to improve their thermal, mechanical, and barrier properties and if their end-of-life phase is included in the LCA study, then they become not environmental sustainable. The bio-based polymers with greater difficulty will biodegrade while the synthetic polymer will lose their recyclability (ExcelPlas Australia, Centre for Design, RMIT & NolanITU, 2004).

With the new technologies is possible to reduce over certain limits the volume and weight of the packaging materials, with a considerable saving on raw material consumption (both renewable than nonrenewable ones) and reduction on solid wastes. But the problem could be the increase on the food damage due to inadequate protection and safety with a consequential increment on the food wastes (Oki & Sasaki, 2000).

To reduce the amount of packaging material one possible solution could be to increase the food packaging size. In this case, more food is packed with reduced use of materials. The problem could be that food could deteriorate faster than in small size packaging, increasing the food wastes, making a less eco-compatible choice (Grönman, 2013).

Thanks to the improvement of the LCA methodology, a large number of research studies were done and published, making the food packaging field the most investigated system (Siracusa et al., 2014). So, in this field, studies can be focalized on the LCA study of food and drink products, food and drink packaging, on alternative food packaging technologies and on food waste, and/or packaging wastes management options, focalized on the end-of-life phases.

Flanigan et al. (2013) as well as Ror et al. (2009) and Grönman (2013), reported several cases studies of LCA analysis for food and beverages and for packaging materials, giving the possibility to understand the environmental performance of this methodology. They compare several studies focalized on food and packaging materials, with the analysis of the end-of-life scenarios, and in same case implementing the comparison between different kinds of alternative materials solution (conventional packaging versus novel packaging). All found that food, especially as wasted food, has more impact than the packages but several articles do not take into consideration the food waste. If the package is seen as a fundamental strategy to reduce the food losses, then food waste must be taken into account. In fact, Williams and Wikström (2011) and Hanssen et al. (2012) write that a real connection between food losses and packaging is very important to stress the important role of the packaging to avoid food wastes.

Biodegradable polymers, recycled materials such as polyethylene terephthalate, biopolymers, edible films, lightweight packaging, and so on have been the object of LCA study in these recent years. In this context, very interesting studies were reported in 2013 by Yates and Barlow (2013), Hottle et al. (2013), and Pawelzik et al. (2013). Leceta et al. (2013) reported a case study of comparison between a 1 m² of chitosan film with 1 m² of conventional polypropylene film used for packaging application. All phases such as material extraction, film manufacture, and end of life were considered. It was evidenced that the raw material extraction phase for the production of the polypropylene film was more environmentally impacting on carcinogen and fossil fuel categories while for chitosan films the phases with most impact were respiratory inorganics, land use, and mineral categories, associated with the nonoptimized film manufacturing phase, which enhanced the consumption of electricity and additives. However, the end-of-life composting scenario was more favorable for the chitosan than for the polypropylene film.

Few articles are present in literature regarding the LCA study on nanomaterials. As an example de Figueirêdo et al. (2012) reported a case study on two cellulose nanowhisker from coconut and from white cotton fibers, with a low environmental impact recorded from the prime films rather than from the latter.

But, not only is packaging the principal contributor to the environmental impacts of a food product. Agricultural production and processing must also be taken into consideration. Erlov et al. (2000) reported that the energy used for processing bread, tomato juice, milk, and yogurt was 68% greater than the energy used for the packaging system. Indeed, as reported by Silvenius et al. (2011),

2%–5% of the total environmental impact could be attributed to the packaging for greenhouse emission, eutrophication, and acidification impacted categories. An opposite tendency is recorded for soft drinks bottle and for low-value food packaging where the materials used for packaging exhibit the greater environmental impact.

7.3 Limits of the LCA Analysis

To best represent the environmental LCA study results, diverse methodological aspects should be improved. First of all, correct strong interaction between food and packaging has to be taken into account. This is to avoid an over or lower estimation of the packaging, to evaluate the correct influence of the packaging in the product life cycle, to evaluate the influence of different packaging materials and packaging technologies (Restuccia et al., 2016). Then, considering that the main feature of a packaging material is to protect, to ensure the food safety and quality and to extend the food shelf life, these aspects must be encountered in the choice of the packaging functional unit. Finally, the most difficult task, a good balance between quality, health, economic, social, and environmental factors must be included in the study. One possibility could be to perform together with the LCA study, a LCC analysis. On this new methodology, called life cycle sustainability assessment, several researchers are already working.

Despite the increase in popularity of this methodology, several other efforts have to be made to overcome its limitations. First of all the study of a product or a package is geographically related, with very different environmental effects. The various packaging functions have to be considered when an LCA study is performed comparing different packaging materials, for the same product, as for example: if one package is reusable or not, if it provides a greater shelf life than the other, if one is more commercial communicative than the other (branding), and so on. The final cost, related to extraction of raw materials, manufacturing, transport, recovery, or disposal is also a very important tool if not of primary importance. Another time, it is necessary to correlate the LCA study with the LCC analysis. The LCA results are most of the time related to the specific system under study and could not be generalized and adapted for every situation. In general the consumer's behavior is not taken into consideration in LCA studies.

Despite these limitations, the LCA methodology is a very helpful tool in the identification of the most used resources and wastes production, on the identification of emission into air, water, and soil. Further it serves as the decision-maker's tool for selecting the best product or process with lower environmental impact. LCA

assesses the waste management options and serves as a valuable decision support tool for policy makers and the industry.

8 Conclusions

Over the past 20 years, many results have been achieved in the study of bio-based materials for food packaging application. Despite that, many of the studied materials remained at the laboratory scale due to several reasons. First of all, the higher cost is compared with synthetic polymers derived from petroleum resources. It is obvious that if the production capacity increases, the costs can fall down. One possibility will be to substitute the production of raw materials with biofuels. The second reason is related to the material performances. Many attempts have been made to improve their properties but, taking into consideration that the main feature must be their degradation, very often it is not possible to improve their properties over a certain limit. Further, as a result of their inherent biodegradation behavior, their functions are active for a short period of time, shorter than conventional packaging, and not adequate to the shelf life request from manufacturers and consumers. Melt extrusion for thermoplastics preparation is sometimes not possible for bio-based polymers, which have to be prepared by a casting procedure, especially for edible films. Inadequate water vapor barrier behavior has limited their application in the food's packaging field but this is an inherent property essential to confer the biodegradability behavior to these materials.

So, to adequately address the stability of these materials to the intended storage and use conditions, much more investigation is mandatory. It is indisputable that the use of bio-based materials will increase in the near future owing to their improved performance such as mechanical and barrier properties. Probably the near future will see these materials blended with other polymers and nanoparticles, obtaining bio-nanocomposite materials, to meet the demand of the food packaging industry for achieving the desired performances required for commercial application.

Further, considering that consumers are asking vociferously for sustainable and environmental friendly food packaging materials, an additional effort is required by the suppliers. The modern industrial economy must be characterized by the development of efficient processes and products, with reduced energy and resources consumption, and decrease in material and energy content. Additional research is required from industries, consumers, and governments to ensure a more sustainable society with a minimum impact on the environment and future generations.

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SUSTAINABLE SANITATION IN THE FOOD INDUSTRY

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1 Introduction

In the food industry, the control of unwanted microorganisms is essential and decisive (Stoica et al., 2011b, p. 291). Contamination of the processing lines is typically induced by the so-called "food soil" that represents any unwanted material (e.g., food residues, food product being handled, carbohydrates and starch residues; proteins such as casein, mineral salts, fat and emulsions, bacteria, fungi, lubricating grasses, inert soils, and so on) on the surfaces of food processing plants (Cullen and Norton, 2012, p. 163; Norton and Tiwari, 2014, p. 363). The soil is deposited on food processing equipment and forms films that negatively interact with the processing integrity lines, for example, on the walls of an empty tank and on the internal surface of a heat exchanger (Norton and Tiwari, 2014, p. 363). These films can also be formed out of deposited water minerals and cleaning compounds as well as biofilms (Jimenez-Pichardo et al., 2016; Norton and Tiwari, 2014, p. 363). The term "biofilm" refers to the microorganisms surrounded in extracellular polymeric substances produced by them. The extracellular polymeric substance protects microorganisms by providing nutrients, blocking antimicrobial action, estranging toxins and metal ions as well as preventing dehydration of cells (Carpentier and Cerf, 1993; Houdt and Michiels, 2010). Biofilms are able to develop and propagate into pipeline surfaces and are very difficult to be removed (Houdt and Michiels, 2010; Norton and Tiwari, 2014, p. 363).

Cleaning and sanitizing of processing lines is a critical step in reducing the risk of transferring pathogenic organisms to food and consumers between different runs (Otto et al., 2011; Stoica

et al., 2010a, 2011a, 2012a,b,c; Lefcourt et al., 2013). Cleaning concerns the removal of unwanted material from food contact surfaces to ensure that they are visually clean, are not malodorous and are not greasy to touch (removes the food soil from the surfaces) (Jimenez-Pichardo et al., 2016; Keener, 2005, p. 447; Norton and Tiwari, 2014, p. 363). The sanitation (disinfection in Europe) is the process of applying a sanitizer against microbial contaminants to ensure that a clean surface is substantially free from pathogenic microorganisms and spoilage microorganisms (Brumă et al., 2011; Gram et al., 2007; Keener, 2005, p. 447; Norton and Tiwari, 2014, p. 363; Stoica et al., 2010b, 2011a). Cleaning and sanitizing procedures should actively destroy the vegetative cells of hazardous microorganisms and substantially reduce the population of other undesirable microorganisms without adversely affecting the food product quality or its safety for the consumer (Damkjær et al., 2017; Jimenez-Pichardo et al., 2016; Jurado-Alamedia et al., 2012; Norton and Tiwari, 2014, p. 363; Pan et al., 2006). These operations are time and energy consuming and have a considerable impact on the environment because of the amount and pollutant content of the generated wastewaters. Therefore, the development of effective and environmentally compatible cleaning and sanitizing procedures is a constant need for the food industry (Jurado-Alamedia et al., 2012).

To develop economically and sustainable cleaning and sanitizing programs, the food processors must consider a wide range of different influencing factors. These include the food contact surface (equipment surfaces, preparation area, conveyors, utensils, and packaging materials), the process temperature, the type of cleaning and sanitizing agents, the contact time, the pH value, the disinfectant's concentration, and the surface's finishing of metallic materials (Brumă et al., 2011; Norton and Tiwari, 2014, p. 364; Stoica et al., 2010a, 2011a). For instance, the sanitizer agents with low pH values cause high corrosion. Indeed, the acidic environments can cause a breach in the protective layer of metallic surfaces, whereas high pH values can decrease metal solubility (Stoica et al., 2011a). The metallic surfaces with a great roughness are easily damaged, while smooth surfaces present better corrosion protection (Stoica et al., 2011a). The soil attached on rough (mechanically sanded or untreated) metallic surfaces would not receive the same cleaning shear forces as soil attached to a smooth (electropolished) surface, as the rough surfaces are much more difficult to clean and sanitize comparing to smooth surfaces (Schlisselberg and Yaron, 2013; Stoica et al., 2011a). Metallic surfaces are acceptable if the arithmetic average height parameter (R_a) (the most universally roughness parameter for general surface quality) is lower than $0.8 \mu\text{m}$ (Holah and Thorpe, 1990; Lee et al., 2010; Stoica et al., 2012c).

After disinfection, the remaining sanitizer agent in the processing food lines serves as a sentinel against unwanted microorganisms (Brumă et al., 2011; Stoica et al., 2011a). However, it is important not to be a chemical risk for consumers' health and not to exceed the legal limits (Brumă et al., 2011; Stoica et al., 2011a).

In addition, the residual sanitizer can potentially lead to a significant degradation of equipment' materials (e.g., stainless steel food grade) via corrosion that, in turn, can increase the adhering of soil and affects the surface cleaning ability (Brumă et al., 2011; Holah and Thorpe, 1990; Leclercq-Perlat and Lalande, 1994; Masurovsky and Jordan, 1958; Otto et al., 2011; Stoica et al., 2011a). Austenitic stainless steels are traditionally used for food industrial applications (Brumă et al., 2011; Stoica et al., 2010a, 2011a). However, these materials have been progressively replaced by ferritic stainless steels that are cheaper due to the absence of nickel (Brumă et al., 2011). The ferritic stainless steel is used for cutlery, kitchen sinks, and catering/gastronomy industry, as well as for food processing industry due to its advantages that includes esthetic quality and low thermal expansion coefficient (Brumă et al., 2011). Acidic and alkaline sanitizers induce numerous structure modifications on austenitic and ferritic stainless steel surfaces (Brumă et al., 2011; Stoica et al., 2011a). For example, Figs. 1 and 2 show the images on the ferritic stainless steel surfaces without sanitizer treatment (Fig. 1) and after

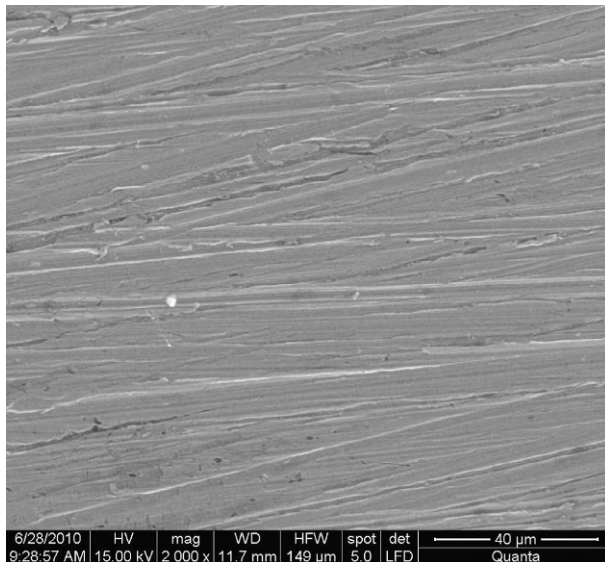


Fig. 1 SEM image on ferritic stainless steel surface without sanitizer.

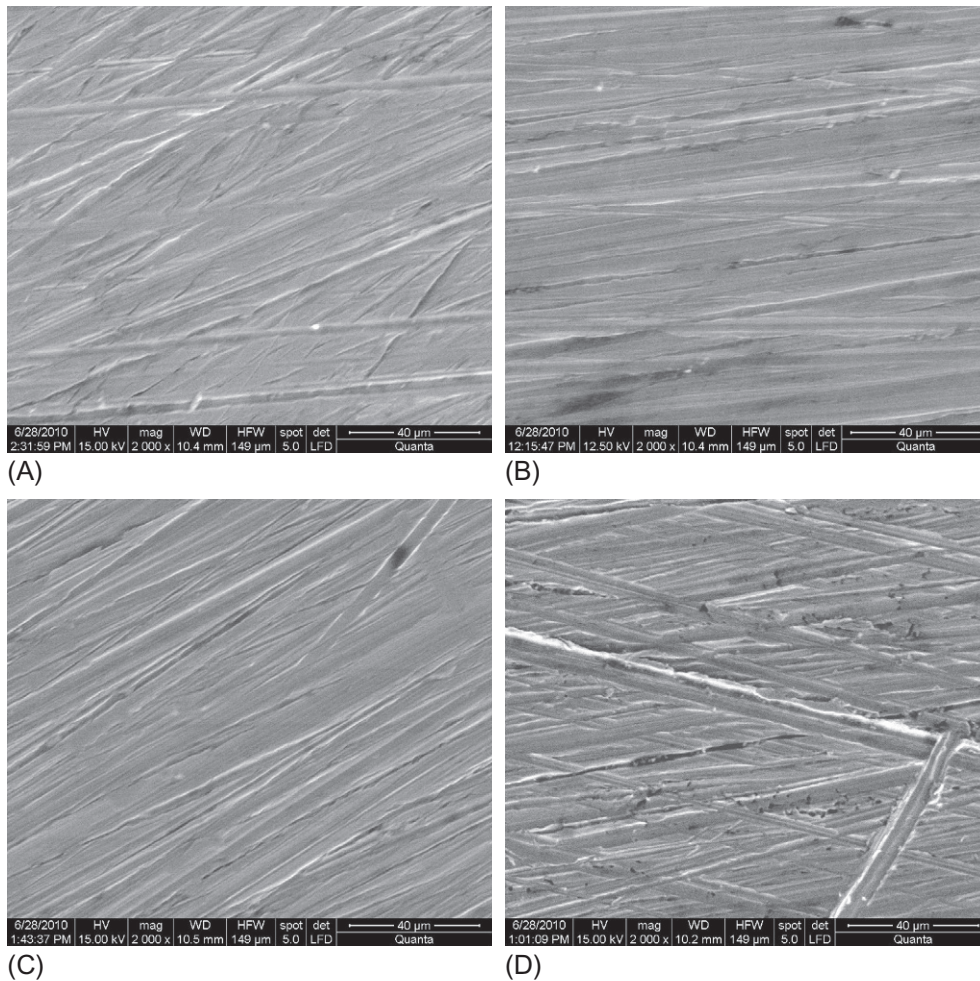


Fig. 2 SEM images on ferritic stainless steel surfaces in low pH sanitizer at different contact time and different temperatures: 30 min, room temperature (A); 480 min, room temperature (B); 30 min, 50°C (C); 480 min, 50°C (D).

exposure to the low pH dilute sanitizer at different contact time and different working temperatures (Fig. 2A–D).

The scanning electron microscopy (SEM) image on the stainless steel without sanitizer illustrates that the surface has a roughness and pit-free nature (Fig. 1). A lower destruction can be observed in the scanning electron micrograph of the stainless steel surface after immersion in dilute sanitizer for 30 min (Fig. 2A). The SEM image on the stainless steel after 480 min of exposure to the dilute sanitizer at 50°C shows the most remarkable changes in the surface roughness that are mainly attributed

to the destruction of the protective layer. This treatment causes serious and numerous pits and valleys (dark areas) (Fig. 2D).

2 Cleaning Procedures

Every production process in the food industry requires different sanitizers, which vary with the type of equipment and the food product type (Stoica et al., 2011a). These characteristics should be considered when selecting the sanitizers for metallic surfaces (Stoica et al., 2011a). The development of cleaning procedures requires significant knowledge of the underlying physicochemical phenomena to ensure a sustainable use of chemical agents, energy, and water during the process (Norton and Tiwari, 2014, p. 364). Over the years, two types of cleaning and sanitizing procedures have emerged: COP (cleaning out-of-place) and CIP (cleaning-in-place), currently in use in the food industry (Keener, 2005, p. 446; Moghaddam et al., 2016; Norton and Tiwari, 2014, p. 364). COP is a very straightforward process consisting of disconnecting or dismantle parts, prerinse dismantled parts, wash prerinsed parts, sanitation, and final rinse (Keener, 2005, p. 446). These basic procedures constitute the fundamental elements of all wet-cleaning processes (cleaning by hand, dish-washing machines). COP is more laborious than CIP. CIP is the most economical approach, taking shorter working time and involving lower costs and labor work (Lorenz, 2005, p. 425; Moghaddam et al., 2016; Norton and Tiwari, 2014, p. 364). The CIP systems are largely used in the food industry for cleaning interior surfaces of equipment without disassembly (Simeone et al., 2016). CIP is now a widely incorporated cleaning approach for almost all dairy, beverage, winery, and processed-food production plants (Lorenz, 2005, p. 428; Norton and Tiwari, 2014, p. 364). The sustainability of the cleaning process depends not only on the type of cleaning strategies, but also on the characteristics of the used agents that should be considered separately for each type of application (Norton and Tiwari, 2014, p. 364). In many cleaning applications, the physicochemical alteration mechanisms are used, whereby the agents interact physically with the food soil through wetting, softening, swelling, heating, and so on (Norton and Tiwari, 2014, p. 364). A chemical reaction (hydrolysis of proteins, saponification of lipids, and decomposition of salts) alters the structure of the soil. Thereby, the fluid flow is the mean that develops enough shear stress to dislodge and subsequently transport the bound soil and at the same time removes microorganisms out of the system to avoid contamination of already cleaned

surfaces (Norton and Tiwari, 2014, p. 364). All the above issues need to be taken into account during cleaning and sanitizing procedures in the food industry (Norton and Tiwari, 2014, p. 364). The effectiveness of the chemical agents is also extremely important, as they must have a high microbial destruction capability against a wide range of microorganisms (Norton and Tiwari, 2014, p. 364). A wide variety of sanitizers (e.g., chlorine reactive species, hydrogen peroxide, quaternary ammonium compounds, and ozone) are currently in use or being evaluated for use in food areas (Brugnoni et al., 2012; Hoelzer et al., 2012; Jimenez-Pichardo et al., 2016; Morente et al., 2013; Stoica et al., 2010a,b, 2011a, 2012a,b,c).

Chlorine is a bactericide that acts on the membranes of microorganisms to inhibit the enzymes involved in glucose metabolism and to oxidize protein within the cell wall (Norton and Tiwari, 2014, p. 364; Stoica et al., 2010a). Chlorine is activated at low temperature, and is economical, leaving small amounts of residue on food contact surfaces (Norton and Tiwari, 2014, p. 364). However, major drawbacks are also associated with chlorine by-products, for example, they are corrosive to many metallic surfaces (especially at higher temperatures) (Norton and Tiwari, 2014, p. 364). Moreover, chlorine can form potentially toxic (carcinogenic) in the presence of organic matter (e.g., trihalomethanes) under certain conditions (Gómez-López et al., 2013; Jimenez-Pichardo et al., 2016; Norton and Tiwari, 2014, p. 364). Although, hazards associated with the formation of carcinogenic substances from chlorine are of public concern, there are not many other suitable chemical sanitizing agents commercially available with such a wide range of microbial action (Norton and Tiwari, 2014, p. 365). In addition, the use of chlorine is also associated with the production of high amounts of wastewater with very high levels of biological oxygen demand (environmental risk) (Olmez and Kretzschmar, 2009).

Ozone is a powerful oxidizing agent with a high antimicrobial activity, while leaving no toxic residues on stainless steel surfaces or foods, but is unstable and decomposes rapidly (Çatal and İbanoğlu, 2014; Meireles et al., 2016; Seckin and Caner, 2014). Higher concentrations are required when it is used as gas, since the humidity of the air affects its penetration into microbial cells and the consequent sanitizing process (Meireles et al., 2016). It can become very toxic as it can affect the respiratory tract and cause irritation to the eyes and throat (Artés et al., 2009; Meireles et al., 2016). Its use is sensitive to the presence of organic matter and it is not suitable to be used on the product, as it can affect its physicochemical properties (Meireles et al., 2016). It is potentially corrosive to the equipment (Meireles et al., 2016).

Organic acids (natural or chemically synthesized) are highly effective (Jimenez-Pichardo et al., 2016). Organic acids have some possible drawbacks such as the change in the flavor of the food product that could influence its sensorial properties (Meireles et al., 2016). Furthermore, when organic acids are used to decontaminate fresh-products, the wastewater may present high values of both chemical oxygen demand and biochemical oxygen demand (Meireles et al., 2016; Ölmez and Kretzschmar, 2009). Other pointed drawbacks are their high cost, the corrosion of the food processing equipment, and the toxic hazard to workers (Jimenez-Pichardo et al., 2016; Meireles et al., 2016; Sagong et al., 2011). These realities, therefore, require the search for alternative cleaning and sanitizing agents effective against food spoilage and pathogenic bacteria, yet harmless to humans and the environment.

Electrolyzed water (EW) is an interesting option, being useful for both cleaning (alkaline water) and sanitizing (acidic water) of food industrial equipment and facilities. EW, a CIP reagent, has the potential to reduce the cost of CIP cleaning (the operational expense of CIP cleaning using EW was 25% less than conventional method). In addition, is noncorrosive (neutral EW and slightly acidic EW) and can be advantageously used for environmentally friendly cleaning and sanitizing processes.

3 Cleaning-In-Place

Developing a sustainable cleaning program promotes and ensures environmental and economic benefits, reduces the impact on the environment, eliminates the use of natural resources and makes facilities greener and healthier. A sustainable cleaning and sanitizing procedure must address the following issues.

Efficient cleaning operations:

- ensure the cleaning procedure efficiently balances the cleaning action due to chemical agent, temperature, and mechanical force;
- schedule the cleaning to happen alongside maintenance routine to ensure that any equipment/facilities taken apart for maintenance can be cleaned simultaneously; and
- train and incentivize staff to clean-as-they-go to reduce build-up, clean-up time, and potential infestations with pest (Norton and Tiwari, 2014, p. 365).

Food consumer safety:

- ensure that high-quality water and sanitizing protocols are used during the cleaning procedure;

- identify high heat and moisture areas in the food factories where the microorganisms build-up can have a significant influence; microorganisms can grow on almost any surface so it is important to identify all food contact surfaces paying particular attention to low-pressure areas where microorganisms build-up is high; and
- regularly swab the surface of the processing plant equipment to check the quality of the sanitizing program when it is required (Norton and Tiwari, 2014, p. 366).

Optimize use of the sanitizers and minimize the waste:

- ensure all waste material disposal routes are short and direct;
- ensure equipment is designed so that an optimal balance is easily found between all the cleaning process;
- staff must be trained adequately to ensure they understand the sanitizers usage policies to minimize occurrences of accidental food contamination to reduce contamination or spills and ensure notices are visible to advise where maintenance activities are on-going; and
- try to use programs that have a reduced environmental load (Norton and Tiwari, 2014, p. 366).

In the last years the cleaning and sanitizing techniques of food processing equipment have been perfected (Memisi et al., 2015; Stoica et al., 2013, 2014). In the past, cleaning of the food equipment has been performed by workers who had to dismantle the equipment and enter the reservoir to reach the zone they needed to clean-up (Memisi et al., 2015). The food products were often contaminated by inadequately cleaned and sanitized equipment (Memisi et al., 2015). CIP, adapted to the various parts of the production factory, has been developed to achieve good results in cleaning and sanitizing (Memisi et al., 2015). CIP is generally accepted as being the best approach for cleaning closed systems in the modern food industry (Lorenz, 2005, p. 425; Norton and Tiwari, 2014, p. 366). CIP, typically starting with a removal of gross debris (generally involves draining the product from the system to be cleaned under gravity, or physically displacing the product; often incorporated in prerinse stage), prerinse (this serves to reduce total water consumption and to utilize any heat energy), detergent recirculation (the soil being lifted from the equipment surface and held suspended in detergent solution), intermediate rinse (serves to remove all traces of detergent), second detergent recirculation (optional) (utilize an acidic cleaner to follow an alkaline cleaner in the first detergent circulation), second intermediate rinse (with potable water), sanitation (with an oxidizing sanitizer or hot water than a chemical agent), and final rinse

(Berg et al., 2017; Khalid et al., 2014; Marriott and Gravani, 2006; Simeone et al., 2016). Alkaline washing is done to remove proteins and fats, which are alkaline soluble, from equipment surfaces (Speers et al., 1984). The cleaning mechanism of alkaline solutions primarily relies on hydroxyl ions (OH^-). These ions attack the solid-liquid interface on the surface where the pH is above 10; hence, proteins placed on the surface become negatively charged, and repel each other and get swelled of proteins. Acid-based cleaning, usually performed to remove the inorganic matters, follows alkaline cleaning. After the cleaning steps, some residual microorganism can remain and survive on food processing equipment, thus sanitization inactivates them prior using the equipment. However, a CIP process is designed differently for each processing plant, to avoid prolonged down time, over use of water and chemical wastage during cleaning (Khalid et al., 2014). The CIP system can be defined as circular washing, with fluid (mix of chemicals, heat, and water) running through tubes and machines (pipes, pumps, valves, tanks, heaters separators, vessels, process equipment, etc.) and through the stages of enclosed machines because it is too expensive to disassemble and open them frequently (Hou et al., 2016; Memisi et al., 2015; Norton and Tiwari, 2014, p. 366).

To ensure that the cleaning and sanitizing process is efficient and cost effective and therefore sustainable it is essential to optimize all energy usage throughout CIP system (Norton and Tiwari, 2014, p. 366). The energy input into a cleaning process can be summarized by means of the Sinners diagram which illustrates the main parameters (chemical fluid, fluid mechanics, cleaning temperature, and cleaning time) that need to be applied at different magnitudes (Goode et al., 2013; Lorenz, 2005, p. 426; Norton and Tiwari, 2014, p. 366). The cleaning temperature and the chemical agent flow are the most effective methods to distribute temperature and chemical agent throughout the equipment to be cleaned (Goode et al., 2013; Norton and Tiwari, 2014, p. 367). Higher temperatures provide higher solubility of soluble soils and increase the chemical reaction rate of cleaning solution and soil. Consequently, higher temperatures lower surface tension, increase pH and decrease viscosity. Consequently, a higher cleaning and bactericidal action can be performed (Marriot and Gravani, 2006). Mechanical force occurs as a direct influence of the flow, because of the force dragging the dirt away from the surface (Norton and Tiwari, 2014, p. 368). The cleaning force is fluid flow that enables removing the soils. The effective cleaning in CIP requires turbulent flow, which is achieved by increased fluid flow velocity (Dunsmore et al., 1981). The important aspect is the

contact time expected and at the required temperature and concentration (Goode et al., 2013; Norton and Tiwari, 2014, p. 368). Running the solutions for longer time, when other parameters are kept constant, can enhance the effectiveness of CIP. The longer contact times during CIP runs, the more efficient the cleaning it provides (Dunsmore et al., 1981). Instead of using the term mechanical action alone, hydrodynamics is the appropriate term to use regarding cleaning rate and microbial removal (Norton and Tiwari, 2014, p. 368). The hydrodynamic effect is determined by a combination of flow velocity, fluid exchange, fluctuations and disturbances and wall shear stress (Norton and Tiwari, 2014, p. 368). The concentration of cleaning solutions can be increased until an optimized value (based on the recommendation of the supplier) to increase the efficiency of the cleaning. However, it is the least effective of the parameters to improve cleaning efficiency (Marriot and Gravani, 2006).

The velocity field of the fluid plays a central role in affecting biofilm structure and other soil constituents as the shear stress must exceed adhesion and cohesion forces of different soils to facilitate cleaning (Hall-Stoodley and Stoodley, 2002; Norton and Tiwari, 2014, p. 368; Pereira et al., 2002; Purevdorj-Gage et al., 2006; Stoodley et al., 1999; Tsai, 2005; Vieira et al., 1993). The local fluctuations in the wall shear stress can improve the clean ability particularly where sudden and gradual pipe diameter changes occur. The best cleaning is obtained when the mean wall shear stress is either above a predefined local fluctuations in wall shear stress (Norton and Tiwari, 2014, p. 368). Increasing the pumping speed is not a good way to improve the cleaning as it accentuates the difference between the high-velocity and low-velocity regions of the flow—thereby reducing the shear stress in places where it is required (Norton and Tiwari, 2014, p. 369). It has even found that pulsations at a relatively low flow velocity results in a good cleaning efficiency, highlighting both the economic and environmental benefits that can be derived from this approach (Norton and Tiwari, 2014, p. 369). What is important to state is that the total amount of energy put into a specific cleaning and sanitizing process always remains the same (Norton and Tiwari, 2014, p. 367). This means that a reduction in magnitude of one parameter has to be compensated by an increase in one or more of other parameters (Norton and Tiwari, 2014, p. 367). In food industrial process, the geometry of processing equipment and pipework tanks is usually complex and hydrodynamics of the cleaning and sanitizing fluid varies due to bends joints (Blél et al., 2007; Lelièvre et al., 2002; Norton and Tiwari, 2014, p. 367). The ends, cracks, corners, crevices, gaskets, valves, and joints are

the vulnerable points for the biofilm formation in food processing lines (Brugnoni et al., 2012; Norton and Tiwari, 2014, p. 367). The wall shear stress can be calculated using the volumetric flow rate, which might be reasonable for straight-piped systems (Norton and Tiwari, 2014, p. 367). However, this is not suitable for systems where the piping network is complicated (Norton and Tiwari, 2014, p. 367). In that case, an averaged wall stress can yield to incorrect results and therefore biofilm build-up can occur, cause adverse effects on processing equipment (Norton and Tiwari, 2014, p. 367; O'Brien et al., 2007). Having an ineffective CIP process the sustainability of the cleaning process is obviously reduced from many points of view: chemical inputs are not used effectively and direct energy inputs for pumping and heating the cleaning agent are ineffectively used, and public health can be compromised (Norton and Tiwari, 2014, p. 367).

There are two types of CIP systems simple closed systems (washing by circulation), appropriate for devices with limited volume (e.g., plate heat exchangers, filters, and chargers) or little CIP systems for so-called *lost washing* for each wash a new cleaning solution is prepared, and the automatic CIP system conducts return of the washing solution (Memisi et al., 2015). The advantages of CIP procedures for cleaning and sanitizing of equipment, machinery, and pipelines, which are washed in food industry are: controlled costs—lower labor costs, the controlled use of resources for sanitizing, water, and energy; greater safety—fewer manual operations, removal of the human factor errors, and safety at work; higher quality of sanitizing—control of the washing is implemented via the control panel and the results are reproducible (Gillham et al., 1999; Memisi et al., 2015). The transition of fluid over surfaces of equipment at high speeds creates the effect of mechanical friction that releases dirt deposits (Memisi et al., 2015). The food industry uses a variety of equipment, the design and the volume of the internal parts or surfaces have to be monitored, and it is difficult to run only circulating washing (Changani et al., 1997; Memisi et al., 2015). The mechanical cleaning is not sufficient but must be augmented with specially designed nozzles for washing (Gillham et al., 1999; Memisi et al., 2015). To have an effective CIP, the equipment must be connected in the cleaning system and must be easy to clean and all surfaces which are washed must be accessible to cleaning agents (Memisi et al., 2015). In addition, the equipment should not have blind ends that chemicals cannot access or through which they cannot run and machines and pipes must be placed so that they can be easily drained (Memisi et al., 2015). All places from which residual water after

washing cannot run off will become a place for microbial growth and cause a serious risk of food product contamination (Christian and Fryer, 2006; Memisi et al., 2015). The materials involved in the food processing equipment, like stainless steel and polymers, must be of such quality that they leave no trace, smell, or taste to the food product (Brumă et al., 2011; Memisi et al., 2015; Stoica et al., 2010a, 2011a). These materials must also be resistant to contact with cleaning and sanitizing agents at the cleaning temperature (Changani et al., 1997; Memisi et al., 2015).

CIP programs differ according to whether circuits include cleaning of the heating surfaces or not and can be divided into the following categories: CIP programs for rotary washing into which pasteurizers and other equipment containing heating surfaces (e.g., UHT—ultra-high temperature) are included and CIP programs for rotary washing which involve tanks for the reception of pasteurized milk with a pipe system (Memisi et al., 2015). These two programs differ in that the acid circulation is always included in the first type to remove deposits of proteins and salts from heating surfaces (Memisi et al., 2015; Sahoo et al., 2008). In some food plants, after washing with water, CIP system is programmed to start rinsing with acidic agents, to remove salt deposits, break-up the layer of soil, and thereby enable the breakdown of the proteins by alkaline chemical agents (Memisi et al., 2015). The pasteurizers are usually cleaned and sanitized in the morning, before the start of production, carried out by hot water circulation at 90–95°C for about 10–15 min just after the temperature has reached at least 85°C (Memisi et al., 2015). If the sanitizing process is performed by chlorine chemical agents, there is a risk of fast corrosion if deposition of acidic sanitizers occurs (Brumă et al., 2011; Changani et al., 1997; Norton and Tiwari, 2014, p. 364; Memisi et al., 2015). Where the cleaning process begins with alkaline and ends with acidic agent, after the final rinse water, the equipment should be rinsed with weak alkaline chemical solution to neutralize acid before sanitizing by chlorine chemicals (Memisi et al., 2015). The conventional CIP systems have four reservoirs: cold water, an acid, a base, and the so-called steamy water and there are systems with another added hot water reservoir (Memisi et al., 2015). In CIP system, there are sensors for measuring the levels, the concentration, and the temperatures of the fluids in each tank, and all signals from the probes and pumps are forwarded to the central computer (Christian and Fryer, 2006; Memisi et al., 2015). All the relevant data of the system can be seen at the terminal, and the operators have the option to select the washing program cycle, generate diagrams, and so on (Memisi et al., 2015). CIP systems are designed to reduce water

consumption in the food industry and provide many advantages such as less chemical substances, reduced time consumption, and decreased labor demands, but it requires a significant initial capital.

4 Electrolyzed Water—Ecologically, Friendly Cleaning, and Biocidal Solution

In the modern food industry, the equipment (robots, processing lines, etc.) comes every day into contact with different products and is, therefore, a potential carrier of food-borne pathogens (Witte et al., 2017). The cleaning and sanitizing procedures for the equipment that comes into direct contact with food products are essential to reduce the risk of product contamination (Carpentier and Cerf, 2011; Olmez and Kretzschmar, 2009; Stoica et al., 2010a, 2011a; Witte et al., 2017). They are performed with different chemical and psychochemical decontamination techniques (Brumă et al., 2011; Stoica et al., 2010a,b, 2011a,b, p. 291; 2012a,b,c, 2013, 2014; Witte et al., 2017). However, some of these techniques possess numerous drawbacks, such as high cost, remaining chemical residues, low efficacy, adverse effects on the quality of food products, and negative impact on the environment because of the potential high volumes of pollution in the generated wastewaters (Al-Haq et al., 2005; Norton and Tiwari, 2014, p. 369; Pascual et al., 2007). Nowadays, specialists are looking for the development of innovative, gently and eco-friendly cleaning and sanitizing procedures. In this line, EW—an eco-innovative sanitizer and cleaner, is currently being seen as a novel technology to meet all of these challenges (Graça et al., 2011). EW is more eco-friendly than NaClO (sodium hypochlorite) and is not potentially harmful for human health (Navarro-Rico et al., 2014). It possesses antimicrobial activity against numerous microorganisms and eliminates most common types of bacteria, fungi (molds and yeasts), viruses, and spores in a relatively short time (5–20 s) in food products, food processing surfaces, and nonfood surfaces (Ding et al., 2015; Hao et al., 2015; Hricova et al., 2008; Huang et al., 2008; Rahman et al., 2016). EW is an effective agent for CIP of food processing and handling equipment and it has been found to be very effective both as a cleaning (alkaline EW) and as a sanitizing agent (acidic EW) (Satyanarayan et al., 2014). Indeed, its application eliminates costly cleaning chemicals and erases many of the dangers associated with storing (Satyanarayan et al., 2014).

4.1 Electrolyzed Water's Production

The electrochemical activation is an electrophysical and electrochemical influence on water that contains ions and molecules of dissolved substances in it. The water is converted into a metastable condition, showing increased reactivity in different physicochemical processes. This process takes place under conditions of minimal heat release in the area of dimensional charge at the electrode surface of electrochemical system at nonequilibrium charge transfer through the interface electrode—electrolyte by electrons ([Electrolyzed Water, 2013](#)). EW is produced in an electrolytic flow cell, which includes a semipermeable membrane that is used to separate the cathode and anode ([Afari et al., 2016](#); [Al-Qadiri et al., 2016](#); [Arevalos-Sánchez et al., 2013](#); [Audenaert et al., 2012](#); [Graça et al., 2011](#); [Hao et al., 2011](#); [Huang et al., 2008](#); [Jimenez-Pichardo et al., 2016](#); [Khayankarn et al., 2013](#); [Liu et al., 2013](#); [Meireles et al., 2016](#); [Torlak, 2014](#); [Wang et al., 2014](#); [Whangchai et al., 2010](#); [Xu et al., 2014](#); [Zhang et al., 2012](#)). The technology produces the cleaning and/or sanitizing agents through the electrolysis of a solution of NaCl (sodium chloride) or Na₂CO₃ (sodium carbonate) ([Electrolyzed Water, 2013](#); [Graça et al., 2011](#); [Jimenez-Pichardo et al., 2016](#); [Meireles et al., 2016](#); [Rahman et al., 2016](#)). A current (8–10 A) is passed through the EW generator and the voltage (9–10 V) is generated between the electrodes ([Al-Haq et al., 2005](#); [Graça et al., 2011](#); [Jadeja and Hung, 2014](#); [Meireles et al., 2016](#); [Rahman et al., 2016](#); [Torlak, 2014](#)). Upon the onset of the electrolysis process, NaCl dissolves in water and dissociates into positive ions (Na⁺) and negative ions (Cl[−]). In the solution, OH[−] (hydroxyl) and H⁺ hydrogen ions are also formed. The negatively ions (Cl[−] and OH[−]) move to anode, where the electrons are released and there are generated HOCl (hypochlorous acid), OCl[−] (hypochlorite ion), HCl (hydrochloric acid), oxygen gas, and chlorine gas. The positive ions (Na⁺ and H⁺) move to cathode, where they gain electrons, resulting in the generation of NaOH (sodium hydroxide) and hydrogen gas ([Al-Haq et al., 2005](#); [Hricova et al., 2008](#); [Rahman et al., 2016](#)). The acidic and alkaline versions are formed simultaneously in each side of the chamber ([Jimenez-Pichardo et al., 2016](#); [Rahman et al., 2016](#)). At the anode, the acidic EW or electrolyzed oxidizing water, an acidic solution (anolyte) with a pH of 2–3, oxidation reduction potential (ORP) >1100 mV and available chlorine concentration of 10–90 ppm are produced ([Al-Qadiri et al., 2016](#); [Graça et al., 2011](#); [Meireles et al., 2016](#); [Ovissipour et al., 2015](#); [Rahman et al., 2016](#); [Torlak, 2014](#)). At the cathode, the alkaline (basic) EW, an alkaline solution (catholyte) with a

pH of 10–13 and ORP of –800 to –900 mV are produced (Graça et al., 2011; Jadeja and Hung, 2014; Meireles et al., 2016; Ovissipour et al., 2015; Rahman et al., 2016; Shimizu and Hurusawa, 1992; Torlak, 2014). A low redox potential shows an excess of OH^- ions that can participate in the formation of more symmetric and weak O—H—O (hydrogen bonds) (Jimenez-Pichardo et al., 2016). Using single-cell chambers, some researchers have reported the generation of Neutral EW with a pH of 7–8 and ORP of 750–900 mV and slightly acidic EW with pH ranging from 5 to 6.5 and ORP of ~850 mV (Al-Haq et al., 2005; Deza et al., 2007; Nan et al., 2010; Rahman et al., 2016). Neutral EW is produced by mixing the anodic solution with OH^- ions or by using single-cell unit (without membrane) from NaCl or HCl, whereas slightly acidic EW is produced by electrolysis of HCl alone or in combination with NaCl in a single-cell unit without membrane (Jimenez-Pichardo et al., 2016; Forghani et al., 2015; Hricova et al., 2008; Meireles et al., 2016; Rahman et al., 2016). Neutral EW is more stable than acidic EW, as chlorine decay occurs at low pH (Jadeja and Hung, 2014; Meireles et al., 2016; Torlak, 2014). EW, produced from regular water without the addition of any harmful chemicals except NaCl, can be stored by conservation in the dark or conversion into ice cubes (Rahman et al., 2016).

4.2 EW's Properties

During the electrolysis, a high amount of available chlorine along with lower amounts of H_2O_2 (hydrogen peroxide) and O_3 (ozone) are produced, having significantly lower adverse effects on the environment (Kim et al., 2000; Rahman et al., 2016). The sanitization effect of EW is influenced by various factors: available chlorine (Cl_2 , OCl^- , HOCl), pH, ORP, current, water flow rate, electrolyte, salt concentration, electrode material, storage conditions, water hardness, and water temperature (Al-Haq et al., 2005; Len et al., 2000; Rahman et al., 2016). The pH of EW plays an important role in the formation of various chlorine species. Available chlorine is strongest in the HOCl form and exhibits 80 times greater sanitizing power than OCl^- when the pH of the solution is 5.0–6.5 (Cao et al., 2009; Rahman et al., 2016). The ORP and available chlorine concentration of EW were found to decline substantially with an increase in pH from the acidic to the alkaline region, where the ability to inactivate of microorganisms was found to be diminished (Rahman et al., 2010a, 2016). The values of ORP, available chlorine concentration and pH increases with increasing in the current value and salinity is linearly correlated to conductivity and there

is a linear correlation between the amount of NaCl added and the amount of HOCl produced during the electrolysis process (Al-Haq et al., 2005; Rahman et al., 2016). The sanitizing applications of EW have been limited, due to the evaporation of Cl_2 over time and the ensuing HOCl breakdown, particularly in open conditions, while when stored under closed conditions, EW loses chlorine by self-decomposition but is, however, lower than the chlorine loss by evaporation under open situations (Al-Haq et al., 2005; Hricova et al., 2008; Len et al., 2002; Rahman et al., 2012, 2016). However, chlorine loss is not affected by lighting during storage, the ORP value remains constant, indicating the existence of other strong oxidants (Bonde et al., 1999; Rahman et al., 2016). High sanitizing activity of EW increases by increasing in the electrolyte concentrations (Forghani et al., 2015; Rahman et al., 2016). Electrode material may influence the production of strong oxidants (HOCl , OCl^- , Cl_2 , OH^- , O_3 , and H_2O_2). The water temperature can influence the antimicrobial efficacy of EW (Cao et al., 2009; Fabrizio and Cutter, 2003; Forghani et al., 2015; Rahman et al., 2010b, 2016). Water hardness is a relatively new concept in EW-related studies and so far, only two studies have examined the influence of water hardness on the sanitizing efficacy of slightly acidic EW (Forghani et al., 2015; Pangloli and Hung, 2013; Rahman et al., 2016). Water hardness has shown a positive impact on the EW antimicrobial effect and is a crucial factor that must be considered in the optimization and production of slightly acidic EW (Pangloli and Hung, 2013; Forghani et al., 2015; Rahman et al., 2016).

EW increases cell microbial membrane permeability and disrupts the cytoplasmic structures, leading to the rapid leakage of intracellular proteins, K^+ and deoxyribonucleic acid and reducing the dehydrogenase activity of microbial cells (Ding et al., 2016; Zeng et al., 2010, 2011). This unique technology produces HOCl, a weak acid but powerful and natural sanitizer that acts rapidly without the need of heating. In addition, it is produced from readily available natural materials and offers a highly sustainable sanitation and cleaning solution. HOCl dissociates to OCl^- at high pH and Cl_2 at low pH values. HOCl has a strong microbial effect (Rahman et al., 2016). HOCl penetrates the microbial cell wall and produces OH^- , which exerts antimicrobial action via oxidation occurring in the key metabolic frameworks (Huang et al., 2008; Stoica et al., 2010a; Rahman et al., 2016). HOCl can penetrate the lipid bilayer of the plasma membrane by passive diffusion (Rahman et al., 2016). The penetration of HOCl is due to its electrical neutrality and its modest molecular size, which is comparable to that of water (Rahman et al., 2016). This is also true for other neutral and small molecules such as H_2O_2 (Rahman

et al., 2016). HOCl can attack the microbial cell not only from the outside, but also within the cell, thereby accelerating the inactivation rate and enhancing the microbial activity (Rahman et al., 2016). Ionized OCl⁻ is unable to penetrate the microbial cell membrane because of the lipid bilayer, which is the hydrophobic layer of the plasma membrane (Stoica et al., 2010a; Rahman et al., 2016). Occasionally, some structures of the microbial cell wall also protect the cell from OCl⁻ penetration; OCl⁻ imparts oxidizing action only from outside the cell (Rahman et al., 2016). In the first step of sanitizing by OCl⁻, the rupture or disintegration of the microbial cell wall appear to occur, and then OCl⁻ inactivates the functional proteins localized in the plasma membrane (Rahman et al., 2016). This is responsible for the poor antimicrobial activity of OCl⁻ (Rahman et al., 2016).

Acidic EW has a strong bactericidal activity due to its low pH, high ORP and HOCl content and acts similar to chlorine (disruption of cell proteins and enzymes) (Meireles et al., 2016; Wang et al., 2014). Acidic EW, due to its low pH, is responsible for the decrease in the production of bacteria (*Listeria monocytogenes*, *Escherichia coli*, *Listeria innocua*, and *Salmonella choleraesuis*) and for making the bacterial cells more vulnerable towards dynamic chlorine by making their external layer more susceptible to HOCl (Graça et al., 2011; Park et al., 2004; Rahman et al., 2016). Acidic EW has higher ORP and lower pH; the high ORP could cause modification of metabolic fluxes and ATP (adenosine triphosphate) production and low pH may sensitive the outer membrane of bacterial cells to the entry of HOCl (Graça et al., 2011). However, it is potentially corrosive for processing equipment and has a short storage life because of the rapid loss of chlorine (Torlak, 2014). Different types of EW act differently when stored under the same conditions. Acidic has been shown to be less stable than neutral EW throughout the storage period (Cui et al., 2009; Nagamatsu et al., 2002; Rahman et al., 2016). Acidic EW stored at 4°C was more stable than when stored at 25°C (Fabrizio and Cutter, 2003; Nagamatsu et al., 2002; Rahman et al., 2016). Storing acidic EW at -18°C may be a good method to retain the available chlorine as well as the bactericidal activity (Xie et al., 2012). However, acidic EW used at 50°C may be a potential method to enhance its bactericidal activity (Xie et al., 2012).

Alkaline EW is produced from the cathode compartment in the electrolytic cell with a membrane and works as a detergent (Meireles et al., 2016; Ni et al., 2016). The alkaline EW features (low redox potential, excess of OH⁻) combined with electrochemically produced NaOH show a high capacity to dissolve mineral deposits (salts and phosphates) and to disrupt biofilms

extracellular matrix (Parkar et al., 2004; Rigdon et al., 2017; Sun et al., 2012). In addition, alkaline EW has antioxidative effects on highly unsaturated fats and oils and has superoxide dismutase-like and catalase-like activities (Ni et al., 2016).

Neutral EW, due to its pH, reduces the risk of corrosion of processing equipment and irritation of skin and has stability during storage as compared to the use of acidic EW (Afari et al., 2016; Monnin et al., 2012; Arevalos-Sánchez et al., 2013; Cui et al., 2009; Guentzel et al., 2008; Jadeja et al., 2013; Jemni et al., 2014; Jimenez-Pichardo et al., 2016; Lee et al., 2014; Meireles et al., 2016; Nagamatsu et al., 2002; Navarro-Rico et al., 2014; Rahman et al., 2016; Torlak, 2014). Neutral EW combines the advantages of both acidic EW and alkaline EW (Monnin et al., 2012; Hricova et al., 2008). It is readily able to penetrate through cell membrane and creates conditions for intensive osmotic and electroosmotic oxidant's transfer into intracellular media (Electrolyzed Water, 2013). The osmotic transfer of oxidants through membranes of microbials' cells is more intensive than through membranes of somatic cells, due to inherent difference in osmotic gradient of these types of cells (Electrolyzed Water, 2013). The electroactive compounds of the medium and the electrically charged cluster structures formed by dissolved gas molecules in water promote high-speed electroosmotic carry of oxidants into the microbial cell, because the clusters produce strong local electric fields with high heterogeneity in zones of contact with biopolymers (Electrolyzed Water, 2013). Neutral EW produces the decarboxylation of amino acids, reactions with nucleic acids and oxidation of key enzymes (Hricova et al., 2008). Neutral EW has been shown to have a longer storage life due to the reduction of chlorine loss at a neutral pH (Monnin et al., 2012). The active ingredients of neutral EW are chlorine-oxygen compounds: O_3 , HOCl and OCI^- . The strong antimicrobial success of neutral EW is mainly due to a combination of some factors: ORP and mixture of metastable chlorine-oxygen compounds (O_3 , OCI^- , HOCl) (Graça et al., 2011; Monnin et al., 2012; Duan et al., 2016). Oxidizing agent's loss is significantly reduced at pH values 6–9 which extends its stability during storage (Aider et al., 2012; Cui et al., 2009). At least 95% of chlorine in neutral EW was in the form of HOCl, which is effective as a sanitizer (Rahman et al., 2010a). Only a small concentration of chlorine-oxygen compounds guarantees for absolute safety of humans and environment under long-term use of neutral EW (Electrolyzed Water, 2013). Total content of active chlorine-oxygen compounds in neutral EW varies from 50 to 500 ppm which is many times lower than in most working solutions of

biocides used nowadays (Electrolyzed Water, 2013). Due to the low content of active substances HOCl and OCl^- , neutral EW is considered nontoxic, therefore there is no need to remove it from treated surfaces after the sanitizing treatment (Electrolyzed Water, 2013). Neutral EW kills the microorganisms of bacterial, viral, and fungus etiology (*E. coli*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, hepatitis B virus, poliomyelitis virus, HIV, adenovirus, pathogens of tuberculosis, salmonellosis, dermatomycosis, and others) (Electrolyzed Water, 2013). A combination of alkaline and neutral EW as alternative agents for automated cleaning and sanitizing in the food industry may be an innovative strategy for CIP automatic process (Jimenez-Pichardo et al., 2016). The combined use of alkaline and neutral EW has the advantages of reducing these agents concentration without decreasing efficiency, low corrosion hazard, nontoxic compounds formation, and no risk of operators skin irritation (Jimenez-Pichardo et al., 2016). Since these treatments do not require rinsing steps while keeping low treatment temperature, they may be sustainable energy saving alternative processes (Jimenez-Pichardo et al., 2016).

Slightly acidic EW contains a high concentration of HOCl (~95%) and its antimicrobial effect, mainly caused by the presence of HOCl, has been proved (Forghani and Oh, 2013; Hao et al., 2013; Ni et al., 2016). It has the advantage of possessing strong bactericidal ability (*Salmonella typhimurium*, *L. monocytogenes*, *E. coli*, *S. aureus*, *Vibrio parahaemolyticus*, etc.), fungicidal, sporicidal and virucidal, with low available chlorine, resulting in reduced corrosion of surfaces and minimization of the potential damage to human health and the environment (Al-Holy and Rasco, 2015; Forghani and Oh, 2013; Issa-Zacharia et al., 2010; McCarthy and Burkhardt, 2012; Ni et al., 2016; Xuan et al., 2017a,b; Zhang et al., 2016). Slightly acidic EW has a similar bactericidal activity with that of NaOH solution (Issa-Zacharia et al., 2010). Therefore, there is growing interest in new applications for the bactericidal activity of slightly acidic EW in the food industry as an environmental friendly sanitization procedure (Forghani and Oh, 2013). Forghani et al. (2015) showed that slightly acidic EW obtained from preheated water (40°C) exhibited substantially higher rates of reduction of bacteria, compared to heated EW (40°C), the phenomenon being attributed to the partial loss of available chlorine that occurs upon heating EW at 40°C. Slightly acidic EW has high stability when stored (Hao et al., 2013). For instance, at a near-neutral pH, it has the advantage of being less corrosive for food equipment and irritating for hands, and minimizing human health and safety (Issa-Zacharia et al., 2010; Ni et al., 2016).

4.3 EW's Advantages and Drawbacks

EW is produced in an environmentally friendly manner from NaCl and distilled water (Hricova et al., 2008; Rahman et al., 2016). It returns to its normal form after usage and poses no threat to humans and the environment (Al-Haq et al., 2005; Rahman et al., 2016). Humans are unaffected by exposure to EW, as long as it is not orally ingested and their eyes are not exposed (Rahman et al., 2016). The main advantage of EW is its ability for on-site production, thus circumventing problems associated with chlorine during transport, storage and handling (Jeong et al., 2007; Rahman et al., 2016). EW is active against a broad spectrum of bacteria and possesses nonselective antimicrobial properties, whereas it is hypothesized that this does not promote the growth of bacterial resistance (Hricova et al., 2008; Rahman et al., 2016). In addition, the sensory quality of food products is not negatively affected by the use of slightly acidic, neutral, and slightly alkaline EW (Hricova et al., 2008; Rahman et al., 2016). The cost of chemical salts, the electricity charges and water are the major operating expenses involved in running the EW production machine, besides the initial investment in purchasing the EW generator (Hricova et al., 2008; Rahman et al., 2016). Another advantage of using EW as a CIP reagent is its safety. Using EW for CIP procedures has the potential to reduce the cost of CIP cleaning, too (Al-Haq et al., 2005). For example, the operational expense of CIP cleaning using EW was 25% lower than conventional method. Neutral EW can be used to sanitize food-contact surfaces and is environmentally friendly since it only uses salt and water to produce the chemical solution. Thereby, there are no problems on handling the solution when it comes in contact with organic matter or when diluted with tap water it can be safely discarded (Meireles et al., 2016). In the presence of organic matter, neutral EW generates lower amounts of organochlorinated molecules than NaOCl (Meireles et al., 2016).

The drawbacks that need to be considered include the relatively high initial cost of equipment (Hricova et al., 2008; Rahman et al., 2016), the short shelf life, the tendency for EW to lose its antimicrobial potential quickly, if it is not continuously supplied with Cl_2 , H^+ , and HOCl by electrolysis (Kiura et al., 2002; Rahman et al., 2016), and the corrosion caused by the free chlorine content or high ORP during the use of acidic EW (Al-Haq et al., 2005; Hricova et al., 2008). The work conducted by Ayebah and Hung (2005) showed that the stainless steel presented *outstanding corrosion resistance* when immersed in acidic EW (pH of 2.42, ORP of 1077 mV and 48.66 ppm of chlorine) at room

temperature (22°C), whereas other materials, such as carbon steel, copper, and aluminum were less resistant to acidic EW. Compared to the acidic EW, chlorine water (pH of 8.72, ORP of 656 mV and 49.16 ppm of chlorine) and its modified form by increasing its pH (pH of 6.12, ORP of 774 mV, and 50.39 ppm of chlorine) were less corrosive. The corrosiveness of acid acidic EW was due to its low pH and high ORP. To address this drawback, two potential solutions could be considered: using neutral EW with less corrosive characteristics (pH 7–8, ORP 750 mV, 50–500 ppm of free chlorine, depending on water electrolyzer), which can be produced by mixing acid acidic with alkaline EW after electrolysis (or by using a single electrolysis chamber without membrane) and adding the corrosion inhibitors to the acidic EW.

4.4 Electrolyzed Water's Application on Food Contact Surface

Cleaning and sanitizing of food processing equipment should be optimized to ensure food safety (Rahman et al., 2016). From this point of view, EW has been employed as a novel sanitizing agent to reduce the microbial count on food contact surfaces to acceptable levels (Hricova et al., 2008; Rahman et al., 2016). The effectiveness of neutral or acidic EW has been examined by several researchers and they have been recommended as novel food contact surface sanitizers (Deza et al., 2005, 2007). The use of acidic EW solution has effectively reduced the microbial populations on metallic and polymeric surfaces (Rahman et al., 2016). EW has been approved by United States regulators as a replacement for harmful chemicals and as a green and sustainable solution for use at home and in the industry (Rahman et al., 2016). Many companies are producing EW. These companies claim to produce 100% pure, eco-friendly, nontoxic, and less expensive EW for industrial use, whereas other companies use of EW technology as a sanitation process for CIP applications (Rahman et al., 2016). EW is an environmentally friendly and highly effective solution for CIP technology for industrial use (Rahman et al., 2016). There are diverse points of view on the sanitizing applications and regulations of EW in different sectors around the globe (Rahman et al., 2016). In the European Union, EW can only be applied to drinking water and its use on food products such as meat and fish is not permitted, because of its properties of protein inactivation (Rahman et al., 2016). However, in the United States, it is used for drinking, cleaning, and sanitizing purposes (Rahman et al., 2016). Recently, USDA (United States

Department of Agriculture) approved the application of EW in organic products (Rahman et al., 2016). Many chemical industries do not possess sufficient knowledge on EW, and more advertisement is required to introduce it in the industry (Rahman et al., 2016). Over the next 10 year, most of the food plants will start using EW, owing to its benefits (Rahman et al., 2016).

Superior cleaning and sanitizing without the need for heating offers reduced cleaning times and increased food plant running times (Electrolyzed Water, 2013). Cleaning and sanitizing at ambient temperature reduces the energy consumed for the process. Using just salt and water to create the fluids, both the cleaner and sanitizer are inherently safe and produce a safer, easy-to-handle wastewater stream (Electrolyzed Water, 2013). Typically, the time savings is over 50% and in many cases, this saves hours for CIP (Electrolyzed Water, 2013). For product changeover CIP processes, the typical time for EW is 15 min or less—a significant savings compared to the previous technology which takes around 1 h (Electrolyzed Water, 2013). Traditional CIP technology uses concentrated chemicals shipped to site which are often applied at elevated temperatures. EW is produced on site in volumes to match site demands at any particular time, eliminating waste production, and reducing water consumption (Electrolyzed Water, 2013).

5 Conclusion

Cleaning and sanitizing of processing lines concerns the removal of unwanted material from food contact surfaces to ensure that they are visually clean and substantially free from pathogenic and spoilage microorganisms. Every cleaning and sanitizing process (a large amount of chemicals, energy, and water user) have a negative impact on the environment because of the potential high volumes of pollution in the generated wastewaters. In addition, the sanitizers can potentially lead to a significant degradation of equipment' materials via corrosion. Developing the innovative and eco-friendly cleaning and sanitizing procedures promotes and ensures environmental and economic benefits: reducing the impact on the environment, reducing water consumption, using fewer amounts of chemical agents, reducing the time consumption, optimization of energy usage. Electrolyzed Water (EW)—an eco-innovative cleaner and sanitizer is currently being seen as a novel technology to meet all of these challenges. It possesses antimicrobial activity against numerous bacteria, fungi, viruses, and spores in food products, food processing surfaces

and nonfood surfaces. EW is a CIP reagent that has the potential to reduce the cost of CIP. The neutral EW and slightly acidic EW are noncorrosive and can be advantageously used for environmentally friendly cleaning and sanitizing processes. Using of EW eliminates waste production and reducing water consumption.

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MICROBIAL BIOSURFACTANTS IN FOOD SANITATION

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1 Introduction to Food Sanitation and Safety

Sanitation is a broad subject, principally related to contamination, cleaning, sanitizers, as well as applying these concepts in food processing to attain hygiene and to prevent food spoilage. From the time that the food is produced till the stretch that it is consumed, it is susceptible to contamination from microorganisms that could be risky. Food sanitation is the exercise of subsequent measures to avoid the microbial contamination of food processing. The term “food sanitation” usually brings up guidelines and measures within the food processing sector that are related to the production, packaging, shipping, and transportation. According to United States Food and Drug Administration (US FDA), inappropriate cleaning and sanitization practices for food-contact surfaces in advance to use are witnessed frequently. This demonstrates that suitable execution of cleaning and sanitization practices needs to be improved during inspections and monitoring. Sanitization targets basically pathogenic microorganisms that develop biofilms on food and food-contact planes. Adhesion of pathogens such as *Salmonella* to food processing surfaces is one of the initial observations on bacterial biofilm formation by foodborne pathogens (Duguid et al., 1966). From that time, a huge amount of publications denoted the ability of foodborne pathogens to attach to food processing surfaces. These pathogens include, for example, *Listeria monocytogenes* (Sharma and Saharan, 2016; Sharma et al., 2015), *Yersinia enterocolitica* (Wang et al., 2017), *Campylobacter jejuni* (Brown et al., 2014), and *Escherichia coli* O157:H7 (Wang et al., 2014). The attachment of food pathogenic bacteria to food-contact or food

processing surfaces can lead to possible hygienic complications in the food chain.

2 Bacterial Biofilms

Bacterial biofilms is defined as a thin layer of microorganisms that abide by the surface with extracellularly secreted polymers. Biofilms are the prime phenotype of microorganisms in their natural habitat and environment. Certainly, bacteria living in a biofilm formation can be up to 1000 times more resilient to antimicrobials and antibiotics than the planktonic state of same bacteria (Mc Carthy et al., 2001; Bradshaw et al., 1996). Biofilm developments are considered to be the microorganism's survival approaches as it affords microbial population with imperative benefits comprising (Fig. 1):

- Improved right to use the nutrients (Claessen et al., 2014)
- Protection against toxins and antibiotics (Schwering et al., 2013)

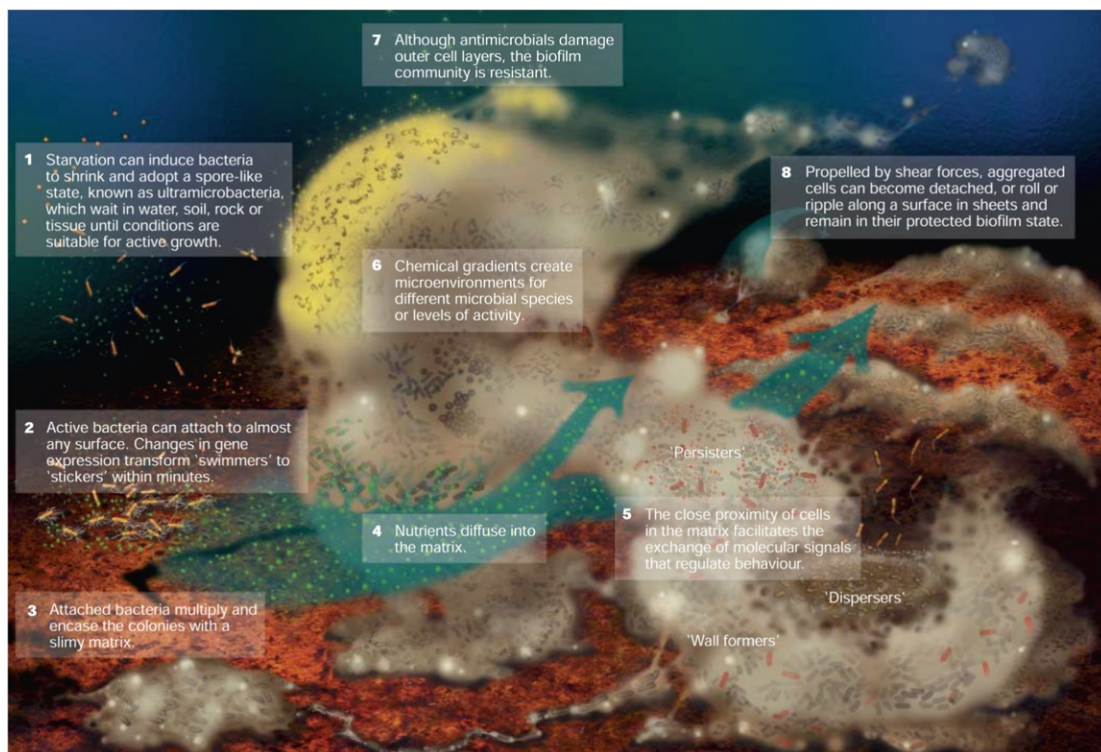


Fig. 1 Conceptualization of biofilm development and dynamic behaviors. Courtesy of Dirckx, Center for Biofilm Engineering, United States.

- Upkeep the extracellular enzyme potential (Okshevsky and Meyer, 2015)
- Protection from predation (Dang and Lovell, 2000)

The initial stage of microbial biofilm formation is adherence over the inert surface and it is regulated by numerous factors: counting type of microbial cell, hydrophobicity of surface and charges of biofilm anchored surface, environmental circumstances, and potential of microorganisms to secrete extracellular polymers, which aid to anchor to surfaces (Zottola and Sasahara, 1994).

More specifically the biofilm formation on any surfaces enters into various phases of microbial survival that include

- Nutrient limitation encourage microbial cell to shrink and survive like a spore state recognized as ultramicrobacteria
- Dynamic planktonic cells anchored surface and initiate production of slimy extracellular matrix
- Nutrient disseminates in matrix and exchange signals that control biofilm establishment
- Chemical gradients make microenvironments for various microbial populations or levels

3 Bacterial Appendages Involved in the Biofilm Formation

Biofilm establishment is related to different cell surface appendages and structures that result in complex communications. For instance, in the case of *E. coli* biofilm development, a widespread network is tangled, which may significantly perform a character in virulence properties. Various cell surface factors play a role in one or more progressive stages of biofilm establishment in *E. coli*. Table 1 provides some of the factors that contribute to biofilm formation. The assistances of the distinct factors or the arising interfaces in biofilm development and simultaneous virulence are challenging to interpret due to the cell-specific surface receptors and factors and the manifestation of multiple types of cell appendages. The latest are subjective to various environmental factors and contests.

4 Biofilm Formation in Food Processing Environments

Bacterial biofilms are predominant moderately on food processing surfaces, tools, and utensils (Maukonen et al., 2003; Sharma and Saharan, 2014). Frequently, surface sanitation is the approach used to reduce surface biofilms by eradicating microbial

Table 1 Bacterial Cell Appendages and Structures Involved in the Biofilms Establishment

S. No.	Microorganism	Factor Responsible for Biofilm Formation	References
1.	<i>Listeria monocytogenes</i>	Flagella, peptidoglycan structure	Todhanakasem and Young (2008) and Monk et al. (2004)
2.	<i>Escherichi coli</i>	Flagella, fimbriae, auto-transporters proteins, extracellular polysaccharides—colanic acid, curli, conjugative pili, exopolysacchrides	Prigent-Combaret et al. (2000), Wang et al. (2004), and Van Houdt and Michiels (2005)
3.	<i>Salmonella enterica serovar Typhimurium</i>	Lipopolysaccharide	Barak et al. (2007)
4.	<i>Yersinia enterocolitica</i>	Flagella	Kim et al. (2008)
5.	<i>Klebsiella pneumoniae</i>	Fimbriae, capsule	Schembri et al. (2005)
6.	<i>Salmonella strains</i>	Capsular polysaccharides	de Rezende et al. (2005)
7.	<i>Aeromonas caviae</i>	Fimbriae	Bechet and Blondeau (2003)
8.	<i>Pseudomonas putida</i>	Fimbriae	Sauer and Camper (2001)
9.	<i>Vibrio vulnificus</i>	Fimbriae	Paranjpye et al. (2007)
10.	<i>Lactococcus lactis</i>	Pili	Luo et al. (2005)
11.	<i>Acinetobacter baumannii</i>	Chaperone-usher pili	Actis-Goretta et al. (2003)

populations developed on food surfaces (Bagge-Ravn et al., 2003). The occurrence of harmful biofilms establishment on surfaces of food processing may lead to the subsequent events:

- Spread of foodborne pathogens
- Advanced food deterioration
- Contagion of food-formulation by nonstarter or nonfunctional strains
- Metal oxidization in food carriage pipelines and storing tanks
- Lessened heat transfer to the industrial vessels

Irrespective of the considerable complications associated to biofilms, the occurrence and predominance of biofilm establishment in food-formulation environments are below par implicit. Thereby, suitable prevention of biofilms formation is quiet thought-provoking. Foodborne pathogens currently indicate a

vital apprehension in food-formulations sector (Sharma and Saharan, 2014; Sharma et al., 2016). A number of food-formulation and processing practices may be accountable for a lower level of food hygiene where bacterial biofilms can embellish ultrafiltration devices, membranes and hollow fibers, rubber or silicone tubing's, and floors (Larsen et al., 2014). Several foodborne pathogens such as *L. monocytogenes*, *L. innocua*, *Salmonella* spp., different species of *Staphylococcus aureus*, and intoxicating pathogens such as *Bacillus cereus* are of vast apprehension in food processing and preparations (Sharma et al., 2015; Beech and Sunner, 2004) (Table 2).

Table 2 Occurrence of Bacterial Biofilm Establishment on Various Food Processing Surfaces

Food Surface	Bacteria Involved	References
Floor drain	<i>Listeria monocytogenes</i> , <i>Salmonella typhi</i> , <i>Pseudomonas fragi</i> , and <i>Leuconostoc citreum</i>	Dzieciol et al. (2016)
Ultrafiltration membrane and hollow fiber	<i>Klebsiella oxytoca</i>	Tang et al. (2010)
Food packaging equipment	<i>Bacillus</i> sp.	Mahalik and Nambiar (2010)
Floors of food processing area	<i>Bacillus</i> sp., <i>Pseudomonas fluorescens</i> , <i>L. innocua</i> , and <i>L. monocytogenes</i>	Carpentier and Chassaing (2004)
Stainless steel pipelines	<i>S. hominis</i> , <i>B. cereus</i> , <i>S. epidermidis</i> , <i>S. aureus</i> , <i>Proteus mirabilis</i> , <i>Serratia marcescens</i> , and <i>Listeria monocytogenes</i>	Ibarreche et al. (2014) and Cherif-Antar et al. (2016)
Dairy plant surfaces and heat exchanging plates and lines	<i>B. cereus</i> , <i>E. coli</i> <i>Shigella</i> sp., and <i>S. aureus</i>	Sharma et al. (2015) and Sharma and Anand (2002)
Conveyor belt or transport lines, salmon processing belts	<i>L. monocytogenes</i> , <i>Shigella</i> sp., <i>B. cereus</i> , <i>Pseudomonas</i> , <i>Stenotrophomonas</i> , <i>Brochothrix</i> , <i>Serratia</i> , <i>Acinetobacter</i> , and <i>Rhodococcus</i>	Langsrud et al. (2016)
Whey processing line	<i>B. licheniformis</i> , <i>B. cereus</i> , <i>B. thuringensis</i> , <i>B. subtilis</i> , <i>B. pumilus</i> , and <i>Paenibacillus glucanolyticus</i>	Cherif-Antar et al. (2016) and Zain et al. (2016)
Dairy utensils and equipment	<i>Listeria monocytogenes</i> , <i>Enterococcus faecalis</i> , <i>Enterococcus faecium</i> , <i>Enterococcus durans</i> , and <i>Enterococcus hirae</i>	Piercey et al. (2016)
Meat processing environments	<i>Salmonella</i> sp.	Wang et al. (2017)

5 Conventional Biofilm Control Approaches

Cleaning and sanitization at food processing surfaces are significant measures, but disinfectants and other cleaning material alone are not competent to eradicate the anchored biofilm and do not prevent the microbial populations to colonize the surfaces (Simões et al., 2010; Sharma and Saharan, 2016). Disinfection, cleaning, or sanitization measures can exterminate around 90% of sessile microbial population, but widespread removal is practically not feasible (Sharma et al., 2015; Taormina and Beuchat, 2002). On the other hand, utilization of disinfectants above the permissible limits eradicates microbial biofilm from food processing surfaces and increases the high risk of residual disinfectants concentration in production area (Ortega-Morales et al., 2013; Torlak and Sert, 2013).

Further substitute for biofilm control strategies such as the use of several proteolytic, cell membrane and cell wall inhibitors, microbial enzymes, lytic bacteriophages, and molecules that can interfere the cell signaling can be used to reduce biofilm establishment (Table 3). Because conventional antimicrobial control procedures fail over and over again to reasonably eradicate anchored bacteria from food-formulation surfaces and production surfaces of utensils and other equipment, novel deterrent strategies have to be developed.

6 Alternative Biofilm Control Approaches

In food processing, microbial surfactants offer various roles and act as emulsifying/foaming agents, antimicrobial, antioxidant material, and antibiofilm agents. A futuristic strategy for contending biofilms establishment is the preacclimatizing of surfaces such as food-formulation/plant surfaces spread over biosurfactants (De Araujo et al., 2011; Sharma and Saharan, 2016; Rautela and Cameotra, 2014). Primarily, biosurfactants were proposed for hydrocarbon removal. However, in the past years, biosurfactants have been considered as replacements material for the control of biofilms, specifically in food-formulations and sanitation (Nitschke and Costa, 2007; Banat et al., 2010). Physical, chemical, and other methods have various drawbacks and are even hazardous to food processing and consumers.

The prevention of microbial biofilms development could be attained through different constituents or modification of their structure on surfaces. Among these approaches, surface accustoming by biosurfactants, comes out to be an effective tactic to

Table 3 Different Approaches Used for Biofilm Control on Food Surfaces

Preventive Methods	Action	References
Physical		
Cleaning and sanitation of food production area or surfaces	Control sporulation in biofilms established by planktonic cells of <i>Bacillus subtilis</i>	Lindsay and Von Holy (2006)
Ultrasound	Enhanced the efficacy of other biocides such as ozone	Baumann et al. (2009)
Ionizing radiation	Disrupt vegetative cells	Niemira and Solomon (2005)
Atmospheric plasma inactivation	Utilization of reactive oxygen and radicals to disable microorganisms	Vleugels et al. (2005)
Cleaning-in-place processes	Blend of food additives, surfactants, and emulsifying agents are being used for improved cleaning procedures	Bremer et al. (2006)
Low-frequency ultrasound	Facilitates passage of antibiotics through microbial biofilms and increases sensitivity of biofilm-growing bacteria to antibiotics	Dong et al. (2013)
Chemical		
Oxidizing agents such as hydrogen peroxide and iodophores	Chemical disinfection	Vlková et al. (2008)
Antifouling coating on metal	Decrease establishment of biofilms	Dong et al. (2005)
PEG-deposition on stainless steel	Decrease attachment	Van Houdt and Michiels (2010)
Bismuth	Antibiofilm agents	Domenico et al. (1991, 1992)
<i>n</i> -Acetyl-L-cysteine (NAC)	Biofilm disruption	Pérez-Giraldo et al. (1997)
Derivatives of 2-aminoimidazoles	Inhibit biofilm formation	Richards and Melander (2009)
Baking soda (sodium bicarbonate)	Antibiofilm agents	Gawande et al. (2008)
Carvacrol	Reduces biofilm formation by <i>Chromobacterium violaceum</i> , <i>Salmonella typhimurium</i> , and <i>S. aureus</i>	Burt et al. (2014)
Detergents containing chelating agents	Disruption of biofilms	Camper et al. (1985)
Oxidants such as per acetic acid, chlorine, iodine, and hydrogen peroxide	Block biofilm formation of <i>L. monocytogenes</i>	Oh and Marshall (1992)

Continued

Table 3 Different Approaches Used for Biofilm Control on Food Surfaces—Cont'd

Preventive Methods	Action	References
Biophysical and biochemical		
Ultrasound with enzyme provisions	Eradicating <i>E. coli</i> biofilms on metal sheets in milk processing	Oulahal-Lagsir et al. (2003)
Biological		
Proteolytic enzymes and bacteriocins	Wide antibacterial spectrum	Gálvez et al. (2007)
Nisin-incorporated PET bottles	Decreased the total microbial load	Guerra et al. (2005)
Bacteriophages	Lytic or lysogenic lifecycle	Kutter et al. (2010), Nobrega et al. (2015), and Sun et al. (2013)
Dnase I	Degradation of DNA leads to modifications in biofilm manner, leads to antibiotic diffusion	Tetz et al. (2009)
DspB	β - <i>N</i> -Acetylglucosaminidase dissolve the biofilm environment	Darouiche et al. (2009)
α -Amylase	Antibiofilm agents	Kalpna et al. (2012)
Garlic (ajoene extract)	Ajoene inhibits production of rhamnolipid biosurfactant	Jakobsen et al. (2012)
Hamamelitannin	The willow bark extract inhibits QS	Morgan (2015)
Flavonoid phloretin	Subdued biofilm establishment of <i>E. coli</i> O157:H7	Lee et al. (2011)
Proanthocyanidins (PACs) e.g., Cranberry	Reduced biofilms deposition	La et al. (2010)
Chlorogenic acids (CGA), largely from coffee	Antibiofilm activities against <i>Stenotrophomonas maltophilia</i>	Karunanidhi et al. (2012)
Boswellic acids	Prevented biofilms established by different species of <i>S. aureus</i>	Raja et al. (2011)
Wheat bran extract	Destroying preformed prevented biofilms established by mastitis causing bacteria	González-Ortiz et al. (2014)
Aspirin	Control the molecules participated in biofilm matrix	Dotto et al. (2017)
Formic, capric, undecylenic acid, and lauric acids	Interruption of biofilms established by <i>Candida albicans</i>	McLain et al. (2000)
Extracellular polysaccharides (EPS)	Inhibits cell signaling of bacteria, avoiding biofilms formation	Karwacki et al. (2013)
4-Phenylbutanoic acid, obtained from <i>Bacillus pumilus</i>	Decrease in <i>S. aureus</i> and <i>Serratia marcescens</i> biofilm deposition	Nithya et al. (2011)
Enzymes of <i>Streptococcus salivarius</i>	Inhibit the formation of dental biofilms	Ogawa et al. (2011)
Lactoferrin	Antibiofilm activity	DePas et al. (2012)

Table 3 Different Approaches Used for Biofilm Control on Food Surfaces—Cont'd

Preventive Methods	Action	References
Antimicrobial Peptides (AMPs)	Eradicate the biofilm establishment by <i>Streptococcus mutans</i>	Sun et al. (2013)
Enzyme- <i>N</i> -acetylmuramide glycanohydrolase	Inhibit biofilm formation of <i>Pseudomonas aeruginosa</i> , <i>Pseudomonas fluorescens</i>	Liu et al. (2014)
Indole derivatives	Decrease <i>E. coli</i> O157:H7 biofilm formation	Lee et al. (2007)
Ginger extracts	Antibiofilm activity against Gram positive bacteria and Gram-negative bacteria	Kim and Park (2013)
Chelerythrine	Control of biofilm development of <i>S. aureus</i> and <i>S. epidermidis</i>	Artini et al. (2012)
Brominated alkylidene lactams	Antibiofilm	Pereira et al. (2014)
Skylamycins	Activity against <i>P. aeruginosa</i> strain PAO1	Navarro et al. (2014)
<i>N</i> -Acyl homoserine lactones	Intermediate quorum sensing in Gram-negative bacteria	Geske et al. (2005)
Microbial amyloids	Antibiofilm activity	Blanco et al. (2012)
Carolacton	Reduced <i>S. mutans</i> biofilms	Jansen et al. (2010)
Cationic peptides	Block biofilm formation by <i>P. aeruginosa</i>	Overhage et al. (2008)
Ionic liquids	Antibiofilm properties	Carson et al. (2009)
Bacteriocins	Lowered the incidence of surface contamination by <i>L. monocytogenes</i>	Bower et al. (1995)

contest biofilm establishment (Meylheuc et al., 2001). In addition to the preapplication of surface commonly exploited for coating on biomedical devices, biosurfactants can also be employed in the pretreatment of food processing surfaces. Food-concomitant pathogens can establish biofilms on food processing surfaces that are more resilient to traditional antibiotics than free-living planktonic microbial cells (Kim et al., 2006; Sharma et al., 2015). Pretreatment of food surfaces such as stainless steel with microbial surfactants obtained from *Pseudomonas fluorescens* diminished the microbial populations of *L. monocytogenes*. The adhesion of the different *Listeria* sp. has been observed after the preconditioning of the stainless steel surfaces with surface-active agents derived from *Lactobacillus helveticus* (Meylheuc et al., 2006). Except the biosurfactant obtained from the probiotic bacteria, various other microbial strains were also observed with similar potential such as rhamnolipids and surfactin. Rhamnolipid and

surfactin are being examined for their possible antibiofilm potential against the several food-associated pathogens to polypropylene and metal surfaces (Nitschke et al., 2009). Preconditioning with biosurfactants prompted a deterioration in the magnitude of anchored biofilms on metal surface. The application of biosurfactants on polystyrene surface reduced the populations of biofilm formers to polystyrene surfaces. In addition, the antimicrobial chacterers of biosurfactant obtained from *Lactobacillus paracasei* exhibited significant antibiofilm potential against several foodborne pathogens such as yeast *Candida albicans*, *S. aureus*, *S. epidermidis*, and *S. agalactiae* (Gudiña et al., 2010). Biosurfactants involved in reduction of microbial populations on various food-associated surfaces are shown in Table 4.

The mechanisms of biofilm prevention by biosurfactants are below par assumed. According to McLandsborough et al. (2006), surface-active agents has to tamper biofilm matrix and reduce the interfacial tension amongst solid surface and biofilm and thus, eliminate biofilm. An additional prospect is that biosurfactants act as wetting agents approving the dissolution of exopolysacchrides matrix (Fig. 2). Fig. 2 shows the influence of rhamnolipid action on *S. aureus* biofilms developed on polystyrene surface. In view of these properties, we can accomplish that microbial surface-active agents are appropriate mixtures for the expansion of approaches to prevent biofilm on surfaces exploited for industrial food processing (Fig. 3). Various biosurfactants derived from different microbial strains were utilized to control the biofilm formation on food and medical surfaces and effectively combat the biofilm development. From GRAS status Lactobacilli to soil-borne and opportunistic pathogens are involved in biosurfactants production and controlling the biofilm formation on various surfaces. Biosurfactants showed potential applications in cleaning various food surfaces such as stainless steel, polystyrene surfaces, heat exchangers, and food transporting pipes and lines. Their applications of biosurfactants showed and advocated an effective utilization in dairy, meat, and other food processing sectors. Generally, the biosurfactants regarded as less toxic by origin, but still their toxicity needs to be determined for their successful applications in food processing and formulations.

7 Conclusion and Future Prospects

Efforts on using biosurfactants in food processing have increased over the past decade since they can be utilized in various modes to prevent the microbial biofilm formation, for

Table 4 Biosurfactants Mediated Reduction of Microbial Populations on Various Food Surfaces

Microbe(s) Producing Biosurfactants	Against Which Pathogen(s)	Food or Industry in Which it is Found	References
<i>Lactobacillus fermentum</i> and <i>Lactobacillus acidophilus</i>	<i>Enterococcus faecalis</i>	Glass surface	Velraeds et al. (1996)
<i>Streptococcus thermophilus</i>	<i>Streptococcus</i> sp.	Heat-exchanger plates in pasteurizers	Busscher et al. (1997)
<i>Pseudomonas fluorescens</i>	<i>L. monocytogenes</i>	Stainless steel and PTFE	Meylheuc et al. (2001)
<i>Pseudomonas fluorescens</i>	Stainless steel	Antibiofilm	Dagbert et al. (2006)
<i>Pseudomonas aeruginosa</i>	<i>Candida tropicalis</i> , <i>Staphylococcus epidermidis</i> , <i>Staphylococcus aureus</i> and <i>Streptococcus salivarius</i>	Silicone rubber voice prostheses Industry	Rodrigues et al. (2006b)
<i>Streptococcus thermophilus</i> A	<i>Rothiadentocariosa</i> and <i>Staphylococcus aureus</i>	Silicone rubber voice prostheses industry	Rodrigues et al. (2006a)
<i>P. fluorescens</i>	Stainless steel	Anticorrosion	Dagbert et al. (2006)
<i>Lactobacillus helveticus</i>	Stainless steel	Antibiofilm	Meylheuc et al. (2006)
<i>Lactobacillus acidophilus</i>	<i>Staphylococcus aureus</i> and <i>Staphylococcus epidermidis</i>	Clinical surfaces	Walencka et al. (2008)
<i>Bacillus licheniformis</i>	<i>Escherichia coli</i>	Water and health-care industry	Rivardo et al. (2009)
Surfactin and rhamnolipid	<i>L. monocytogenes</i> , <i>Enterobacter sakazakii</i> , and <i>Salmonella enteritidis</i>	Polypropylene and polystyrene	Nitschke et al. (2009)
<i>Pseudomonas aeruginosa</i>	<i>E. sakazakii</i> , <i>L. monocytogenes</i> , and <i>S. enteritidis</i>	Stainless steel and polypropylene surface	Nitschke et al. (2009)
<i>Lactobacillus paracasei</i> sp. <i>paracasei</i> A20	<i>S. aureus</i> , <i>S. epidermidis</i> , and <i>Streptococcus agalactiae</i>	Polypropylene surface	Gudiña et al. (2010)

Continued

Table 4 Biosurfactants Mediated Reduction of Microbial Populations on Various Food Surfaces—Cont'd

Microbe(s) Producing Biosurfactants	Against Which Pathogen(s)	Food or Industry in Which it is Found	References
<i>Lactobacilli</i> sp.	<i>Candida albicans</i>	Hospitals (associated with Catheter Associated Infections, Urinary Tract Infections and Medical Devices)	Fracchia et al. (2010)
Lipopeptide biosurfactant <i>Lactobacillus</i> sp.	<i>E. coli</i> <i>Listeria monocytogenes</i> , <i>Salmonella Typhimurium</i> , and <i>Escherichia coli</i> O157:H7	Antibiofilm Food industry	Rivardo et al. (2010) Gómez-Estaca et al. (2010)
Surfactin and rhamnolipid	<i>Staphylococcus aureus</i> , <i>Listeria monocytogenes</i> , and <i>Micrococcus luteus</i>	Polystyrene surface	Zeraik and Nitschke (2010)
<i>Pseudomonas aeruginosa</i> and <i>Bacillus subtilis</i>	<i>Listeria monocytogenes</i> and <i>Pseudomonas fluorescens</i>	Food industry	De Araujo et al. (2011)
<i>Serratia marcescens</i>	<i>Candida albicans</i> , <i>Pseudomonas aeruginosa</i> and <i>Bacillus pumilus</i>	Water and health-care industry	Dusane et al. (2011)
<i>Lactobacillus acidophilus</i> , <i>Lactobacillus fermentum</i>	<i>Streptococcus mutans</i>	Dental clinic	Tahmourespour et al. (2011a,b)
<i>Trichosporon montevidense</i>	<i>Candida albicans</i>	Dental clinic	Monteiro et al. (2011)
<i>Bacillus licheniformis</i> V9T14	<i>Escherichia coli</i>	Hospitals (associated with Catheter Associated Infections)	Rivardo et al. (2011)
Rhamnolipids and surfactin	<i>L. monocytogenes</i>	Polystyrene surface	Araújo et al. (2011)
<i>Robinia pseudoacacia</i> and <i>Nerium oleander</i>	<i>Candida albicans</i>	Hospitals (associated with Catheter Associated Infections)	Cochis et al. (2012)
<i>Bacillus subtilis</i> and <i>Pseudomonas aeruginosa</i>	<i>Staphylococcus aureus</i> , <i>Listeria monocytogenes</i> , and <i>Salmonella enteritidis</i>	Polystyrene surface	do Valle Gomes and Nitschke (2012)
<i>Pseudomonas fluorescens</i> BD5	<i>Escherichia coli</i> , <i>Enterococcus faecalis</i> , <i>Enterococcus hirae</i> , <i>Staphylococcus epidermidis</i> , <i>Proteus mirabilis</i> , and <i>Candida albicans</i>	Hospitals (associated with Catheter Associated Infections)	Janek et al. (2012)

<i>Pseudomonas aeruginosa</i>	<i>Rhodococcus erythropolis</i>	Fuel industry (biodegradation of aromatic compounds)	Schreiberová et al. (2012)
<i>Paenibacillus polymyxa</i>	<i>Bacillus subtilis</i> , <i>Micrococcus luteus</i> , <i>Pseudomonas aeruginosa</i> , <i>Staphylococcus aureus</i> , and <i>Streptococcus bovis</i>	Water and health-care industry	Quinn et al. (2012)
<i>Saccharomyces cerevisiae</i>	<i>Candida albicans</i> and <i>Bacillus subtilis</i>	Dairy industry (dairy wastewater)	Johny (2013)
<i>Bacillus subtilis</i>	<i>Listeria monocytogenes</i>	–	Sabaté and Audisio (2013)
<i>Bacillus subtilis</i> subsp. <i>subtilis</i>	<i>Listeria monocytogenes</i>	–	Sabaté and Audisio (2013)
<i>Pseudomonas aeruginosa</i> DSV20	<i>Candida albicans</i>	Hospitals (associated with Catheter Associated Infections) and oil treatment industry	Singh et al. (2013)
Rhamnolipids	<i>Alternaria alternata</i>	Postharvest control	Yan et al. (2014)
<i>Lactobacillus jensenii</i> and <i>Lactobacillus rhamnosus</i>	<i>Acinetobacter baumannii</i> , <i>Escherichia coli</i> , and <i>Staphylococcus aureus</i> (MRSA)	Hospitals	Sambanthamoorthy et al. (2014)
<i>Providencia rettgeri</i> , <i>Psychrobacter</i> sp., <i>Bacillus flexus</i> , <i>Bacillus anthracis</i> , <i>Psychrobacter</i> sp., and <i>Bacillus pumilus</i>	<i>Pseudomonas aeruginosa</i>	Water and health-care industry	Padmavathi and Pandian (2014)
<i>Oceanobacillus iheyensis</i>	<i>Staphylococcus aureus</i>	Water and health-care industry	Kavita et al. (2014)
<i>Nocardia</i> sp.	<i>Vibrio</i> sp.	Water industry (aquaculture)	Kiran et al. (2014)
<i>Kocuriarosea</i> strain	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	Hospitals (medical devices)	Kumar and Sujitha (2014)
<i>Bacillus amyloliquefaciens</i> strain	<i>Candida albicans</i>	Hospitals (associated with catheter associated infections and medical devices)	Rautela et al. (2014)
<i>Ochrobactrum</i> sp. strain	<i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , <i>Micrococcus luteus</i> , <i>Escherichia coli</i> , <i>Klebsiella planticola</i> , <i>Pseudomonas aeruginosa</i> , and <i>Candida albicans</i>	Hospitals (associated with catheter associated infections, urinary tract infections and medical devices)	Kumar et al. (2014)
<i>Lactobacillus plantarum</i> CFR 2194	<i>Escherichia coli</i> , <i>E. coli</i> , <i>Salmonella typhi</i> , and <i>Staphylococcus aureus</i>	Antimicrobial activity	Madhu and Prapulla (2014)

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Table 4 Biosurfactants Mediated Reduction of Microbial Populations on Various Food Surfaces—Cont'd

Microbe(s) Producing Biosurfactants	Against Which Pathogen(s)	Food or Industry in Which it is Found	References
<i>Candida bombicola</i>	<i>Bacillus subtilis</i> , <i>Cupriavidus necator</i> , <i>Bacillus subtilis</i> , and <i>Staphylococcus aureus</i>	Hospitals (medical devices) and health-care industry	De Rienzo et al. (2015)
<i>Bacillus subtilis</i>	<i>Escherichia coli</i> , <i>Enterobacter cloacae</i> , <i>Citrobacter freundii</i> , <i>Klebsiella pneumoniae</i> , <i>Pseudomonas aeruginosa</i> , <i>Serratia marcescens</i> , <i>Proteus mirabilis</i> , <i>Providencia stuartii</i> , <i>Morganella morganii</i> , <i>Enterococcus faecalis</i> , <i>Staphylococcus aureus</i> , and <i>Staphylococcus epidermidis</i>	Hospitals (associated urinary tract infections)	Moryl et al. (2015)
<i>Bacillus thuringiensis</i>	<i>Fusarium oxysporum</i>	Biodiesel and soap industries	Deepak and Jayapradha (2015)
<i>Bacillus cereus</i>	<i>Staphylococcus aureus</i> , <i>Pseudomonas aeruginosa</i> , and <i>Klebsiella pneumoniae</i>	Hospitals (medical devices)	Hassan and Mohammad (2015)
<i>Lactobacillus acidophilus</i>	<i>Serratia marcescens</i>	Hospitals (medical devices)	Shokouhfar et al. (2015)
<i>Lactobacillus pentosus</i> , <i>Lactobacillus plantarum</i>	<i>Bacillus cereus</i> and <i>Pseudomonas aeruginosa</i>	Food and agricultural industry	Khiralla et al. (2015)
<i>Arthrobacter</i> sp. B4	<i>Pseudomonas aeruginosa</i> PAO1	Water and health-care industry	Li et al. (2015)
<i>Corynebacterium xerosis</i> strain NS5	<i>Staphylococcus aureus</i> , <i>Streptococcus mutans</i> , <i>Escherichia coli</i> , and <i>Pseudomonas aeruginosa</i>	Hospitals (associated with catheter associated infections and medical devices)	Dalili et al. (2015)
<i>Lactobacillus brevis</i>	<i>Candida albicans</i>	Silicone elastomeric disks industry	Ceresa et al. (2015)
<i>Bacillus subtilis</i>	<i>Legionella pneumophila</i>	Hospital	Berjeaud et al. (2016)

<i>Enterococcus faecalis</i> MSI12	<i>Candida albicans</i>	Hospitals (associated with catheter associated infections and medical devices)	Kiran et al. (2015)
<i>Enterococcus faecium</i> MRT19 Sphorolipids	<i>Bacillus cereus</i> <i>Escherichia coli</i> , <i>Pseudomonas aeruginosa</i>	Polystyrene surface Antibiofilm	Sharma et al. (2015) De Rienzo et al. (2015)
<i>Bacillus cereus</i> SNAU01	<i>Pseudomonas aeruginosa</i> and <i>Escherichia coli</i>	Agro-industry	Nalini, et al. (2016)
<i>Lactobacillus helveticus</i>	<i>Escherichia coli</i> , <i>Staphylococcus aureus</i> , <i>Pseudomonas aeruginosa</i> , <i>Bacillus cereus</i> , and <i>Candida albicans</i>	Silicone device industry	Sharma et al. (2016)
<i>Lactobacillus</i> spp. (<i>Lactobacillus plantarum</i> and <i>Lactobacillus brevis</i>)	<i>Escherichia coli</i> , <i>Bacillus cereus</i> , <i>Staphylococcus aureus</i> , <i>Candida parapsilopsis</i> , and <i>mycotoxigenic fungi</i>	Food industry	Cornea et al. (2016)
<i>Bacillus amyloliquefaciens</i>	<i>Vibrio paraheamolyticus</i>	Sea food industry	Thongjun et al. (2016)
<i>Pseudomonas stutzeri</i>	<i>Pseudomonas aeruginosa</i>	Clinical, food industry, and marine industry	Wu et al. (2016)
<i>Pontibacter korlensis</i> strain SBK-47	<i>Bacillus subtilis</i> , <i>Staphylococcus aureus</i> , <i>Salmonella typhi</i> , and <i>Vibrio cholerae</i>	Hospital and water industry	Balan et al. (2016)
<i>Bacillus licheniformis</i> T14	<i>Escherichia coli</i> , <i>Klebsiella pneumoniae</i> , <i>Pseudomonas aeruginosa</i> , and <i>Staphylococcus aureus</i>	Health clinic	Spanò et al. (2016)
<i>Pseudomonas aeruginosa</i> and <i>Burkholderia thailandensis</i>	<i>Bacillus subtilis</i>	Health clinic	De Rienzo et al. (2016)
<i>Rhodococcus ruber</i> IEGM 231	<i>Arthrobacter simplex</i> , <i>Bacillus subtilis</i> , <i>Brevibacterium linens</i> , <i>Corynebacterium glutamicum</i> , <i>Micrococcus luteus</i> , <i>Escherichia coli</i> , and <i>Pseudomonas fluorescens</i>	Hospital and glass industry	Kuyukina et al. (2016)

Continued

Table 4 Biosurfactants Mediated Reduction of Microbial Populations on Various Food Surfaces—Cont'd

Microbe(s) Producing Biosurfactants	Against Which Pathogen(s)	Food or Industry in Which it is Found	References
<i>Starmerella bombicola</i>	<i>Staphylococcus aureus</i> and <i>Escherichia coli</i>	Hospital (associated with catheter associated infections and medical devices)	Phillips (2016)
<i>Lactobacillus reuteri</i> , <i>Lactobacillus acidophilus</i> , <i>Lactobacillus rhamnosus</i> , and <i>Lactobacillus paracasei</i>	<i>Streptococcus mutans</i> and <i>Streptococcus oralis</i>	Hospital	Ciandrini et al. (2016)
<i>Candida bombicola</i>	<i>Salmonella</i> spp. and <i>Listeria</i> spp.	Food industry	Zhang et al. (2016a,b)
<i>Bacillus subtilis</i>	<i>Escherichia coli</i> , <i>Serratia marcescens</i> , <i>Enterobacter cloacae</i> , <i>Proteus mirabilis</i> , <i>Citrobacter freundii</i> , and <i>Enterococcus faecalis</i>	Hospitals (associated urinary tract infections)	Bernat et al. (2016)
Sophorolipids	<i>Escherichia coli</i> O157:H7	Antimicrobial	Zhang et al. (2016a,b)
<i>Bacillus licheniformis</i>	Methicillin-resistant <i>Staphylococcus aureus</i>	Antibiofilm	Coronel-León et al. (2016)
<i>Lactobacillus helveticus</i> MRTL91	<i>Bacillus cereus</i>	Polystyrene surface	Sharma et al. (2016)
<i>Lactobacillus casei</i>	<i>Staphylococcus aureus</i>	Hospitals (associated with catheter associated infections, urinary tract infections and medical devices)	Merghni et al. (2017)

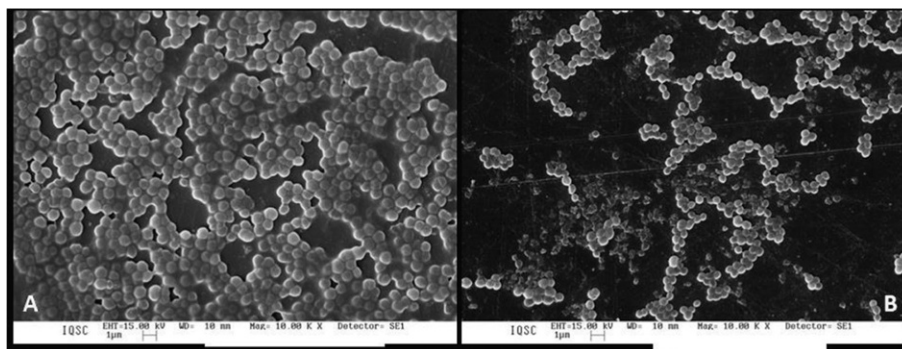


Fig. 2 SEM image of biofilm retardation by rhamnolipid biosurfactants after 2 h treatment at 37°C. (A) Control without rhamnolipids. (B) After treatments with rhamnolipids. Courtesy by Nitschke, M., Silva, S.S.E., 2016. Recent food applications of microbial surfactants. *Crit. Rev. Food Sci. Nutr.* (in press).



Fig. 3 Antiadhesive and antibiofilm mechanisms of biosurfactants action.

example, control on food utensils, preconditioning of food surfaces, biofilm disruption and removal from food lines/surfaces, and retarding biofilm formation of food packaging machines. Nevertheless, their effective exploitation commands further work, giving emphasis on *in vivo* toxicity. In fact, the major constraint on consuming microbial-derived products is the concern about their safety. Some biosurfactants are obtained from opportunistic bacteria, thus the quest for nonpathogenic strains such as yeasts and other GRAS strain is a choice for food applications till date; the approval to utilize biosurfactants from regulatory agencies is still questionable and unanswered. Indeed, there are no guidelines or regulations to exploit biosurfactants in food processing surfaces as next generation food sanitation agents. Since no relevant guidelines are available, biosurfactants

application to food systems should meet at least the guidelines of food additives as suggested by US FDA. In particular, before selecting any molecule as food additive, the following points need to be considered according to [USFDA \(2017\)](#):

- Provide evidence of claimed activity at the intend level of use
- Toxicology data
- Preferably qualify as safe (GRAS) status
- Animal testing data

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PART

C

SUSTAINABLE FOOD WASTE MANAGEMENT

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FOOD WASTE VALORIZATION

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1 Introduction

A sustainable food system, which is mainly based on public health, environmental, and economic aspects, carries a vital importance for humankind survival. In the food systems, the way of production and distribution, as well as the kind of foods we consume can have a certain effect on the planet where we are living on and the society which we are living in. Air, water, land, climate conditions, and biodiversity are the major driving forces for human well-being and, at the same time, major parts of our lives are exposed to human activities intentionally. Sustainability of these natural sources plays a primary role in the food systems. However, food system itself also has a primary role for protecting natural sources because of its certain consequences such as greenhouse gas (GHG) emissions, water and soil pollution, and deforestation (Garnett, 2013).

In the 21st century, food policies take a novel form around nutrition and sustainability terms (Lang & Barling, 2013). A sustainable food system provides healthy, nutritious, and enough food for both current and future generations, with an equally accessible and affordable manner, while at the same time protecting a healthy ecosystem and encouraging local production and distribution, as well as protecting farmers, workers, consumers, and communities (Story et al., 2009). As it is seen from the definitions, sustainability in food systems closely refers to food security and these two concepts should be evaluated as prerequisites to each other (Prosperi et al., 2014). Nowadays, the definition of food security focuses on the access to food rather than food production. In November 1999, The World Food Summit took place with a participation of 185 countries and the European Community for the eradication of hunger. According to definition

of World Food Summit (FAO, 1996), food security is met when “all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life.” Food and nutrition security are considered as the priorities of food system outcomes and strongly emphasized in the definitions of “sustainable diet” that is comprised of a healthy diet and a healthy environment (Allen & Prosperi, 2016).

In June 2009, an Expert Meeting was convened in Rome and FAO (2009) published a document entitled “How to Feed the World in 2050” involving the major findings of the meeting. One of the important conclusions of this meeting was about the necessary increase in food production to 70% by 2050 to feed the world population that is getting larger, more urban, and richer. In addition, this increase must be complemented by policies to achieve food security. However, although an impressive increase in food production was achieved until today, the undernourishment also increased and food insecurity became a reality for 1000 million people (Lundqvist, 2010, p. 75). At the same time, obesity, diet-related chronic disease, and malnutrition became major concerns in the developed countries such as The United States (Story et al., 2009). Because of all these signs of unsustainability, the future of food industry is a major concern of today’s societies, and food waste generation throughout the food supply chain carries crucial importance due to its huge quantity and huge impact on sustainability of environment, economy, and society.

According to Final Project Report of the Government Office for Science (Foresight, 2011), the population increase at global level, the changes in demands per capita, the challenges in the governance of global food system, climate change, competition for resources (such as land, water, biodiversity, and energy), and the changes in consumer behaviors and beliefs, were described as the important drivers of change that are affecting the food system. Besides, the report also determined five challenges for the future of food systems, and food waste took an important place in these challenges. An obligatory reduction in food waste was emphasized in many parts of the reports involved in:

- (i) balancing future demand and supply sustainably,
- (ii) reducing GHG emission,
- (iii) protecting and maintaining of biodiversity and ecosystem, and
- (iv) developing of effective policies in the global food system as a priority for policy makers.

The food industry in today's world feels the pressure of competitiveness, efficiency, sustainable management, and customers who are becoming very sensitive about environmental and social issues. In addition, laws, regulations, and standards are getting stricter, especially in the field of food waste management. Food waste valorization may be a key solution for depressurization of all this pressure and a chance for meeting increasing demand associated with materials, chemicals, and energy as a novel feedstock in terms of its characteristic features (i.e., renewable, available at different amounts, available at different types, and containing functional compounds) (Lin et al., 2013). All these global drivers direct to a biobased economy, which should be taken into account for a sustainable 21st century. Furthermore, traditional meaning of food processing that is aiming to supply a transformation of raw materials into products while focusing in quality, safety, and nutritional aspects must be expended as containing valorization of food waste as well as decrease in energy and water consumption (Lin et al., 2014).

2 Food Waste Valorization

As a consequence of processing raw materials, the production of waste (product specific or nonproduct specific) is an unavoidable result as well as the desired final products. When the food industry is discussed, the variety of wastes such as fruit and vegetable wastes, meat and fish processing wastes, aqueous wastes such as whey, wastewater from industry, and so on can be evaluated as advantage or disadvantage according to the targets. The waste management is an inevitable problem for most of the industries in terms of the today's world that has to protect environment and production sustainability simultaneously. The considerable contribution of food industry to the climate change that is a very serious problem for all humankind cannot be ignored by policy makers. The GHG emissions from food supply chain are produced during all stages of the food production and food consumption. Besides, for developed countries, food supply chain contributes between 15% and 28% to overall national emissions, while 31% of the total GHG impact for EU-25 rise from food according to an analysis for Europe (Garnett, 2011). For the food industry, this inevitable responsibility must be taken into consideration by all participants during the food supply chain. In recent years, this concern became a major driving force to reduce the volume of food waste as well as evaluating it as a renewable feedstock for the production of energy and chemicals. Except

the animal-derived by-products, food waste involves a considerable amount of lignocellulosic material that makes it possible to use for the biofuels. In addition, several processing techniques, especially the extraction, find a large scale of utilization for the production of bioactive compounds, nutraceuticals, and phytochemicals as a renewable source is not only for food industry but also for drug and cosmetic industries. But, the necessary implementations must put into practice after a comprehensive evaluation because of the specific character of food wastes. As a result of high amount of organic material, the management of food wastes must focus on certain difficulties such as high water content, fragile biological stability, oxidation, enzymatic activity, and the likes (Russ & Meyer-Pittroff, 2004).

Throughout the waste management literature, current/or traditional waste valorization practices are known as landfill, animal feed, fertilizer supply, composting, incineration, and anaerobic digestion (Lin et al., 2013). While landfill and incineration are the least desirable options for the legislators and current legislations on waste management, anaerobic digestion is one of the waste treatment methods that can be utilized for the production of heat, energy, and also biofertilizer from both plant- and animal-derived food wastes. Also, composting is a widely used technique for the treatment of municipal wastes from restaurants, canteen, kitchen, and so on.

Although basic valorization strategies are mostly accepted worldwide and they find a wide range of application in general, their capacity to recover and their effectiveness to create value from wastes remain quite limited. The food waste that are generated in high quantities every day, the increasing need for chemicals, materials, and fuels to offer a sustainable future, and the environmental concerns that are getting stronger day by day in our society are the major indicative factors to put into practices for more advance strategies in recent years. Less gas emissions from landfills, less competition for fuels, less ethical conflicts in the case of using nonfood crops, more food supply, more preservation for natural resources, more cost saving routes for surplus, and more specific investments for novel technologies are some of the benefits that can arise from an effective waste management strategy (Fig. 1).

For this purpose, chemical, biochemical, and thermochemical conversion strategies, extraction, fermentation, and enzymes technologies are the main routes followed by researchers and food producers. In addition, biorefinery concept, as an underdevelopment approach in the waste management, offers remarkable opportunities to valorize biomass by converting it to a wide range

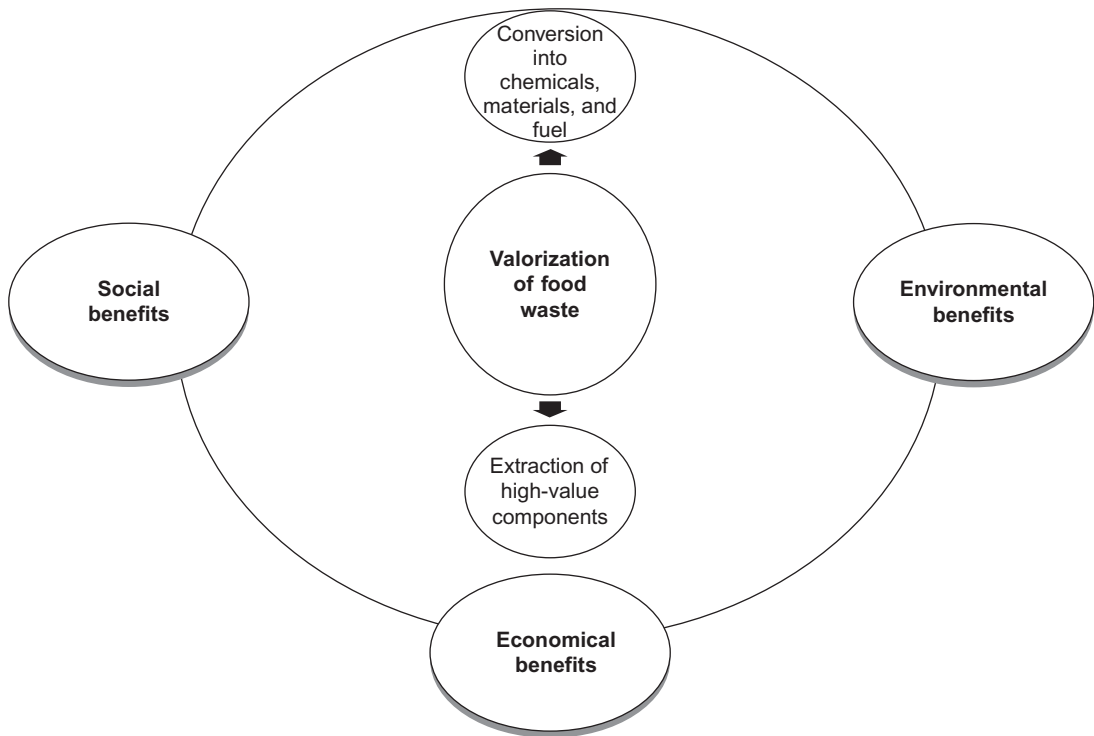


Fig. 1 Valorization of food waste.

of chemicals and fuels. The following section describes the basic and advanced valorization strategies for a sustainable and efficient waste management approach for food industry.

2.1 Landfill

Landfill, as a most common disposal process for municipal solid wastes, involves physical, chemical, and microbial stages during the degradation of the waste. It starts with an aerobic phase and continues under several stages as following: an anaerobic phase (fermentation), initial methanogenic phase, and a stable methanogenic phase. For long time periods, an additional oxidation phase may also be discussed (Kjeldsen et al., 2002). The decomposition of biodegradable compounds, for instance cellulose and hemicellulose, leads to the emergence of powerful GHGs (methane and carbon dioxide) along these stages and landfill process is no longer a valid option for legislators aiming to develop a sustainable economy due to its environmental effects.

Furthermore, they have focused on deterrent actions by means of regulations, taxation policies, and the awareness raising for both public and industry. European Landfill Directive (1999/31/EC) aims to reduce the amount of biodegradable waste sent to landfills to 65% by 2016 compared with 1995 level. In addition, it is estimated that there will be a 90% reduction in food waste going to landfill by 2020 (in comparison with 2006 amount) as a result of a combination of waste diversion policies, which are Landfill Directive, Waste Framework Directive, and future biowaste legislation following from the EC communication ([Anonymous, 2010](#)).

Although there are major advantages associated with landfill application such as low cost and suitability for all kinds of wastes, it is clear to realize that there is a strong pressure applied by both government and public on the food industry to move away from landfill applications for higher value-created, waste treatment strategies.

2.2 Animal Feed and Fertilizer Supply

Following their characteristic features (e.g., rich in protein and fat, high in energy content, and containing fiber and minerals), food wastes and by-products are used as a livestock feed by farmers for a very long time. Its environmental and public benefits as well as the positive effect on animal production cost are the major supportive factors for the expanding of this strategy. The food wastes with high protein and fat content can be suitable for omnivores, while high cellulose and hemicellulose content are only suitable for ruminants and feeding purposes. Besides, food wastes involving high mineral content can be used as fertilizer ([Russ & Schnappinger, 2007, p. 11](#)).

Oil cakes (by-products generated from oil extraction) can be used as animal feed in the case of edible cakes or, alternatively, they are used traditionally as fertilizer due to their mineral content if they are nonedible ([Ramachandran et al., 2007](#)). Biodegradable municipal wastes are also utilized as an animal feed after a proper drying process to overcome chemical and microbiological contamination, high moisture content, and high biodegradability ([Pinacho et al., 2006](#)). In addition, fish wastes ([Arvanitoyannis & Kassaveti, 2007](#)), the by-products of malted barley, milling by-products of wheat and rice ([Krishna & Chandrasekaran, 2013, p. 312](#)), the wastes from potato industries ([Padmaja & Jyothi, 2013, p. 397](#)), and silage of the sugarcane top and molasses ([Murugan & Ranjit Singh, 2013, p. 421](#)) are some of the industrial wastes utilized for the production of animal feed. But in recent years, the events such as the mad cow disease or bovine

spongiform encephalopathy (BSE) crisis and the possibility of presence the toxins or pathogens in animal feeds created major concerns and strong restrictions for the diversification of food processing waste into animal feed.

2.3 Composting

Composting, which requires solid or semisolid waste materials with certain physical and chemical properties, is a waste management method based on aerobic biological degradation. Under suitable conditions (i.e., temperature, pH, moisture content, oxygen content, and C:N ratio) for microbiological activity, this method may supply a volume reduction in waste material by up to 40% while destroying pathogens and weed seeds in the final solid-like product (Schaub & Leonard, 1996).

As a basic valorization strategy, composting is performed by farmers for many years aiming to improve soil structure, to enrich their fields through providing organic materials that rich in nutritional substances and to disinfect as a result of high temperature. During the composting, a fast thermophilic phase is followed by a slower mesophilic phase and, the process can continue from several weeks to a few months (Shilev et al., 2007). In spite of certain benefits of composting such as environment friendly nature, being a driving for to divert practices from landfill and fertilizer supply, the profitability and valorization degree of waste material are some of the topics that must be evaluated about this strategy. For composting process, as well as other basic valorization techniques (aerobic digestion, animal feed, incineration, etc.), scale-up and commercialization stages have already been accomplished because of the utilization of these techniques for a long time. But, a huge amount of food waste is produced dramatically every day and this reality requires the treatment facilities to have enough capacity. As a result, the facilities require a remarkable initial investment together with other challenges such as collection and transportation that may increase the cost and time. Furthermore, variability of quality in final products associated with diverse composition of food wastes can affect the market competitiveness of the compost or animal feed (Arancon et al., 2013).

2.4 Anaerobic Digestion

Anaerobic digestion is a remarkable treatment technique aiming to recover energy (biogas) from organic wastes and wastewater. Degradation of organic materials under anaerobic conditions produces biogas in gaseous form, which mainly consists of CH_4

and CO₂, trace amount of H₂S and NH₃, and a nutrient rich fertilizer in liquid form. The composition of generated biogas depends on the composition of waste such as carbohydrate, fat, and protein content (Koseva, 2013, p. 28).

Anaerobic digestion can be evaluated in four stages. At the beginning of the process, a hydrolysis step involving the breakdown of large and complex components into smaller ones to transport and utilize them into microbial cells is realized. In the following stages, which are called acidogenesis and acetogenesis, acid-forming bacteria produce hydrogen, carbon dioxide, and organic acids from monosaccharides, amino acids, fatty acids, and so on. In the last step (methanogenesis step), methane formation that is produced by methanogens via using acetic acid, formic acid, hydrogen and carbon dioxide occurs at a lower rate than acid-forming stage due to the sensitivity of methane-forming bacteria against the environmental conditions (Hansen & Cheong, 2007, p. 616).

Although anaerobic digestion offers important benefits such as renewable energy production, an effective wastewater treatment, and relatively less cost, the process requires strict control due to its nature. The variations in system inputs caused a decrease in process efficiency, nonlinear nature, complex process kinetics, the difficulty of keeping the process stable, and having effective process control schemes are the main factors limiting the industrial applications (Méndez-Acosta et al., 2004; Tartakovsky et al., 2002).

2.5 Incineration

Incineration, as a conventional waste treatment method, is based on thermal processing result in heat production and combustion products such as gases and ash. The process involves a complete oxidation at 870–1200°C and produces carbon dioxide and water as gaseous products together with small amount of carbon monoxide, nitrogen oxides, and some other organic or inorganic compounds. Incineration can be carried out near the field of waste collection and methane formation does not occur during the process unlike landfill. In addition, it is one of the best options for hazardous wastes to get a sterile ash product (Arvanitoyannis et al., 2008, p. 353). As incineration has a low efficiency in energy utilization, the generated heat can be used in steam turbines and heat exchangers in the industry. Despite having the described benefits, incineration is a suitable application when the water content of the waste is relatively low. Since food wastes generally have a high moisture content and contain combustible compounds, incineration is not always practicable for waste treatment

in food industry. Furthermore, emissions are also an issue to be considered as well as hazardous pollutants (TSP and dioxins) (Digman & Kim, 2008).

2.6 Biorefinery Concept

After realizing that to gain the ability of meeting the demands of future generations together with the present needs over the worldwide, “sustainability” term must be a common issue to be agreed on while building our economy, society and environment for present and near future. Sustainability requires using sustainable resources and sustainable resources requires being renewable. From this point of view, it is clear that the consumption of fossil fuels and other petroleum derivatives must be reduced gradually and replaced with renewable sources such as biomass evaluated as a potential feedstock for industrial productions during past decade.

Biomass is biological raw materials and an alternative for fossil carbon sources. Its composition similar to petroleum but more complicated and, an extraction step as petroleum is not needed because of it already exists as a product (Kamm & Kamm, 2004). As a renewable carbon source, biomass gains an important attention for future biobased approaches such as biobased products, bioenergy, and biorefineries.

The concept of biorefinery is based on the conversion of biomass by separating it into its building units such as proteins, carbohydrates, fatty acids, and other compounds to produce biofuels, chemicals, and other products involving marketing values (Fig. 2). The biomass, as a feedstock of the biorefinery,

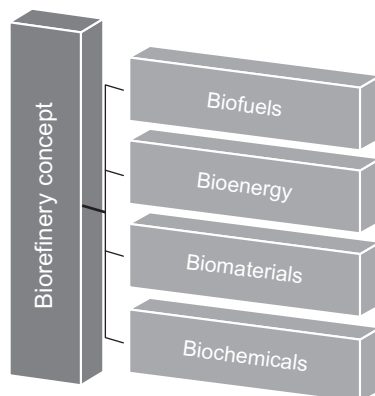


Fig. 2 Biorefinery concept.

mainly categorized into three groups: carbohydrates and lignin, triglycerides, and organic residues which can be obtained from different sources such as agriculture, forestry, industry and household residues, and aquaculture (Cherubini, 2010). The sustainability of biorefineries strictly relies on the availability of biomass. The first-generation feedstock of biorefinery generally contains seeds and grains. The utilization of these dedicated crops such as sugar cane, sugar beet, oil crops (soybean, rape, sunflower, etc.), and starch crops (corn, potato, wheat, etc.) for energy production or chemical production gives rise to a competition between the production of food/animal feed and biorefineries in terms of sharing the natural sources. This competition makes the issue an ethical problem. The food crops and agriculture areas that are diverting for the crop cultivation with the aim of bio-fuel instead of food production create a question mark for a sustainable future. To overcome this conflict, second-generation biomass involving wastes and residues from agriculture, food industry, forestry and nonfood crops are becoming an under developing research field. At the same time, this research field can supply important advantages such as to make the availability of biomass independent from soil fertility and land yields and make it independent from various factors (e.g., climate), to overcome the high cost of production and the difficulties in crop harvesting, to make the storing and transportation more easy, and to enable having a better reduction in GHG emissions (Cherubini, 2010; Wellisch et al., 2010). At this point, food waste that emerges along the whole supply chain and represents a remarkable part of waste issue over the worldwide starts to be seen a truly sustainable feedstock for a biobased improvement in the industry. The third generation (algae) and fourth generation (vegetable oil and biodiesel) are also used as feedstock to attempt the obtaining renewable biofuels in biorefinery (Demirbas, 2009).

Food wastes are traditionally utilized as a chemical feedstock by separation, extraction, or fermentation in the valorization strategies (Mahro & Timm, 2007). However, biorefinery concept needs more integrated approach for taking all advantages of food waste as a feedstock. Vegetable and fruits industry has one of the processing methods which generate large volume of waste along with valuable components such as phenolic compounds, carotenoids, functional compounds, mono-, di- oligosaccharides and so on. To avoid remaining unexploited these valuable material, the processing wastes need an integrated approach in the biorefinery strategy involving; the pretreatment (physical or enzymatic), the extraction of primary natural chemicals (antioxidants, vitamins, pectin, dietary fibers, and the like), the

conversion of primary products into more sophisticated secondary products such as flavorings and building blocks, the continuance following treatments for obtaining feed or bioenergy (ethanol, methane, or hydrogen) from remaining part and finally composting for all residues (Federici et al., 2009). Pourbafrani and coworkers (2010) studied an integrated approach to suggest an industrial configuration for the valorization of citrus wastes. They applied dilute-acid process to hydrolyze citrus waste as a pretreatment and obtained firstly limonene. After centrifugation of slurry, the liquid part was utilized in the fermentation and distillation steps to carry out the production of ethanol. Also, pectin was separated after hydrolysis step by applying a precipitation process. The stillage from distillation step was used for biogas production.

While the conversion of food wastes into valuable products through biorefiners is becoming inevitable because of the critical concerns rising in the society, industry, and governments about the demands for chemicals and fuels, this approach brings along deficiencies and limitations in the application field. A heterogeneous composition with a high water content, fluctuation in volumes based on seasons, low caloric value, the requirements for novel technologies to overcome technical limitations and to find more cost competitive ways and, limited legislative and infrastructure support are some of the challenges that are underlined by literature (Lin et al., 2013).

The conversion of biomass into valuable products via biorefineries needs different technological processes separately or a combination with each other. The extraction of available high-value components from feedstock to use it as a nutritional/pharmaceutical applications or to convert it into other chemicals, materials, or biofuel are the two main routes for biorefineries. The transport difficulties and cost which depends on regional distribution, seasonal amount, and type of food waste, the cost-effective processes which are determined by the degree of homogeneity, the amount and variety of extractable compounds, and security of supply are the factors that affect the competitiveness, production scale, and establishment of biorefinery (Giotto et al., 2015).

Biochemical, thermochemical, and electrochemical conversion as well as chemical processes are the main processes for the conversion of renewable feedstock. In addition, some physical treatments such as raw material pretreatments and the separation procedures can be involved into the process for a comprehensive utilization of biomass in biorefineries (Demirbas, 2009; Ghatak, 2011).

2.6.1 Thermochemical Processes

Thermochemical processes including gasification, pyrolysis, and liquefaction based on heat applications with different amount of oxygen can be utilized to obtain energy and chemicals. Combustion, which is described as a complete oxidation of biomass, and pyrolysis, which is described as a heating of biomass in the absence of the oxygen, constitute two different extreme points of the thermochemical routes. However, gasification process takes place between these two extreme points with various alternative applications (Ghatak, 2011).

Syngas, a gasification product involving in a mixture of H_2 , CO, CO_2 , and CH_4 , can be evaluated as biofuel and also, it can be used as an intermediate product for synthesis other kind of fuels and some chemicals (Cherubini, 2010). Temperature, type of biomass, and the amount of oxygen are some of the factors that are effective on gas composition while gas yield can be maximized by higher temperatures in the gasification process (Ghatak, 2011).

Liquid pyrolytic oil, solid charcoal and light gases (hydrogen, carbon monoxide, carbon dioxide, and methane) can be produced by pyrolysis which is occurred under intermediate temperatures and absence of oxygen (Cherubini, 2010). Lower temperatures and longer vapor residence times are preferred for charcoal production while high temperatures together with longer residence time give rise to an increase in gas production. Also, for liquid product, moderate temperature with short residence time is preferred (Bridgwater, 2012). Although fast and flash pyrolysis approaches represent an alternative and promising technique for the conventional pyrolysis process, microwave-assisted pyrolysis is also a novel approach for the waste treatment applications (Luque et al., 2012). Wheat and corn straw bale (Zhao et al., 2011), coffee hulls, glycerol, and sewage sludges (Fernández & Menéndez, 2011) can be given as examples that were subjected to microwave-assisted pyrolysis in the literature. The results showed that the microwave pyrolysis had remarkable results with higher gas yield, less energy consumption, and less process duration in comparison with conventional pyrolysis. The study of Kantarelis and Zabaniotou (2009) has shown a comparison between fixed-bed air gasification and pyrolysis of cotton stalks. According to the results, high temperature was favored by pyrolysis for a H_2 -rich and CO_2 -reduced gas and the amount of syngas reached a higher maximum concentration by pyrolysis than by gasification with a better quality in terms of syngas and CO_2 .

Lastly, liquefaction that is a conversion of biomass into liquefied products by the catalytic reaction with water and carbon

monoxide/hydrogen can produce valuable bioproducts such as biocrudes. Hydrothermal liquefaction (HTL) including the use of water at high temperature and pressure has very complicated phase equilibria. Biocrude, as a resulting product of HTL, contains a low oxygen content (10–18 wt%) while most of the oxygen is removed from biomass mainly as carbon dioxide (Balat, 2008; Ghatak, 2011).

2.6.2 Biochemical Processes

Bioethanol Production

Production of bioethanol and biodiesel can be given as examples for biochemical conversion processes. For bioethanol production, the usage of biomass such as sugar crops, corn, wheat, rice, and whey is well-established technologies accompanied by certain limitations because of the high-value of these crops for food industry. For this first-generation biofuels which use the seeds, grains, or sugars for substrate, bioethanol production is based on the fermentation of starch or sugars. However, lignocellulosic biomass is another important biomass for the production of bioethanol and this biomass can be used as a substrate for second-generation biofuels. The conversion of lignocellulosic biomass into alcohol is considered more difficult compared with first-generation fuel feedstock. The pretreatment, acid hydrolysis of hemicelluloses followed by enzymatic hydrolysis of cellulose to obtain fermentable sugars and fermentation of these sugars to bioethanol are the main steps of biochemical conversion processes. This kind of conversion needs lower temperatures and proceeds lower reaction rates while the final products have a high selectivity (Demirbas, 2009). The conversion degree of cellulose and hemicellulose into sugar, the combined xylose and glucose fermentation, the lower need for pretreatment step, valorization degree of lignin, and the degree of success in the alcohol separation are the main factors which have an important effect on operational cost of bioethanol production (Naik et al., 2010).

The using of agricultural residues such as wheat and rice straw, corn stover, cotton and barley stalk, and the likes instead of dedicated crops and food wastes has a great potential for bio-refinery feedstock (Cherubini & Ulgiati, 2010; Ghatak, 2011; Öhgren et al., 2007). According to Kim and Dale (2004), wasted crops and residues around the world carry an important potential for bioethanol production. They introduced that the total potential of bioethanol production from crop residues and wasted crops is about 16 times higher than the current world production via 491 GL per year production amount. And this

potential can replace 353 GL of gasoline in the worldwide consumption. Furthermore, the burning of lignin rich residues which is a coproduct of bioethanol production from crop residues and sugar cane bagasse can generate about 3.6% of world electricity production together with 2.6 EJ of steam.

In addition to lignocellulosic biomass, there are several studies that have aimed at a successful ethanol production from municipal food waste and residues in the literature ([Hong & Yoon, 2011](#); [Kim et al., 2008, 2011](#); [Kumar et al., 1998](#); [Yan et al., 2011](#)). Among these studies, the economic value of food waste for ethanol production, pretreatment conditions, the effects of batch or simultaneous process flow, the optimization of the conditions for enzymatic saccharification and fermentation are the main topics which the researchers are focused on. On the other hand, mandarin wastes and banana peels ([Oberoi et al., 2011a,b](#); [Sharma et al., 2007](#)), apple pomace ([Parmar & Vasantha Rupasinghe, 2013](#)), orange peel ([Grohmann et al., 1994](#)), and brewers' spent grain ([Liguori et al., 2015](#)) is the other sources which have been used as a feedstock for ethanol production in the literature.

A bioethanol plant should also consider the production by-products as well as raw materials for a sustainable production. The stillage is the residue which obtained after distillation of the ethanol. The type of feedstock, pretreatment method, and ethanol distillation process can give rise to changes in its composition. The anaerobic digestion can be a good option involving the generation of biogas from the stillage. The stillage has been used as an animal feed in the dried form but the drying process brings an additional and high energy consumption step to the process. Anaerobic digestion of stillage and the production of biogas as a result of this digestion can be used as an energy source for heat or electricity needs in bioethanol plants and this option is becoming an attractive technology for those which desire to obtain a sustainable and green bioethanol production ([Kaparaju et al., 2010](#)).

All these arguments have shown that the availability and feasibility of food wastes aiming at the utilization in bioethanol production should be one of the primary subjects of investigation in biofuel production.

Biodiesel Production

Biodiesel, which is known as monoalkyl esters of fatty acids, has been shown as an alternative energy source to replace petroleum-derived diesel oil since representing a renewable, clean, and reliable biofuel. The transesterification process by using monohydric alcohols and a catalyst (chemical or

enzymatic) is the main route for the production of biodiesel in general. Although biodiesel is an important substitute for diesel fuel, its economic feasibility throws much more attention instead of its certain advantages. The using of alkali catalysis during biodiesel production accelerates the reaction and provides higher yield but also, this kind of reaction is very sensitive the quality and purity of feedstock because of unwanted by-products such as soap. At this point, a high quality feedstock increases the cost of production. If acid catalysts are used to overcome this problem, a lower reaction rates and lower yields are obtained. However, a two-stage reaction including an acid catalysis and after, a base catalysis allows the use of lower grade feedstock (Behzadi & Farid, 2007). Also, transesterification with enzymes, especially with lipases, seems to be an alternative way because of its advantages such as specificity, reuse, genetically engineering option to improve their efficiency and cost, more thermostable structure, and become more natural (Akoh et al., 2007). But optimization of reaction conditions, inhibition the effect of alcohols and cost of enzymes are the main limitation which should carefully take into consideration (Bajaj et al., 2010). Although biodiesel is considered a suitable alternative source for petroleum-derived diesel, high production cost which is mainly due to high cost of raw materials and secondly its production way can make this alternative biofuel uneconomical. The main feedstock for biodiesel production is currently oils or fats in the worldwide. Edible oils such as rapeseed oil, sunflower oil, palm, and soybean oil are the major feedstock of world production. But nowadays, food processing wastes, especially from vegetable oil refineries, meat, and fish processes, other food processes involving any frying step and grease, offer an important alternative feedstock to researchers in terms of their remarkable oil contents (Digman & Kim, 2008). Also, this alternative approach offers an important cost reduction with respect to the manufacturing costs of commercialization of biodiesel production (Kulkarni & Dalai, 2006). However, the microalga with its high lipid content and easy cultivation becomes an alternative approach for biodiesel production in the recent period.

Zhang et al. (2003) studied the comparison between the virgin vegetable oil and waste cooking oil for biodiesel production through alkali and acid catalyzed processes. The results showed that waste cooking oil with acid catalyzed process gave feasible results and less complexity when compared with alkali-catalyzed-process. On the other hand, the usage of the virgin vegetable oil gave rise to a higher raw material cost but supplied a simpler design. Wang et al. (2006) worked on another comparative study

on two different processes involving one-step acid catalyzed and two-step catalyzed with ferric sulfate and potassium hydroxide. The results showed that the two-step approach had important advantages such as high efficiency, low cost, easy recover of catalyst and more environmental friendly with no acidic wastewater compared with acid catalyzed. [Chen et al. \(2009\)](#) also studied on the biodiesel synthesis through catalyzing with lipase in a three-step fixed-bed reactor by using waste cooking oils from restaurants. For more detailed information and examples for the application, a comprehensive review about the production of biodiesel from waste cooking oil which was prepared by [Yaakoba and coworkers \(2013\)](#) can be examined.

The production of biodiesel can represent solely a logical option to petroleum-derived diesel oil when it is evaluated for not only the cost of the raw materials but also the convenience of biodiesel properties for diesel engines without any modification ([Gui et al., 2008](#)). The oil composition and cold flow properties are the mainly important criteria for comparing feedstock oils. For that reason, several studies focused on the conversion of waste edible oils into biodiesel with certain economic and environmental benefits have been done throughout the literature in the past decade. These studies showed that the waste edible oils and also nonedible oils can represent an alternative choice for successful production of biodiesel fuel ([Gui et al., 2008](#); [Kulkarni & Dalai, 2006](#); [Tsai et al., 2007](#)).

2.6.3 Biohydrogen Production

Hydrogen production can be carried out by several ways such as thermochemical processes electrochemical processes, photochemical processes and photocatalytic, or photoelectrochemical processes including direct and indirect approaches ([Balat, 2009](#)). The general source can be fossil fuels in the case of the steam methane reforming process, partial oxidation, or coal gasification processes. Water can be used for the hydrogen production in the case of electrolysis, photolysis, thermochemical process, thermal decomposition, and biological process. On the other hand, gasification and pyrolysis are the two main methods carried out for the utilization of biomass for H₂ production ([Dasa & Veziroğlu, 2001](#)). But in recent years, biohydrogen production through microbiologic activity from renewable organic wastes has been seen as a promising approach for waste treatment applications. As a result of this interest, food waste that has been regarded as an important microbial feedstock for obtaining various bioproducts including enzymes, organic acids, biopolymer and

others, start to be considered as a feedstock for hydrogen production that is an alternative and environmentally friendly energy source. The composition of food waste (especially ones rich in carbohydrate), pretreatments (e.g., heat treatment) and process configuration (e.g., batch, semi- or continuous, single or multistage, organic loading, and acidity of medium) are the main factors that affect the H_2 production from food waste (Kiran et al., 2014).

Biological approach for the H_2 production mainly is realized by anaerobic fermentation and photosynthetic processes. During the anaerobic process, while organic wastes are converting into organic acids and being followed by methane production, hydrogen is produced as a by-product. The pH value of medium and the factors affecting the duration of lag phase such as the composition of substrate and media, temperature and the kind of microbial culture should be considered for desired yield, biogas content, reaction rate, and organic acid produced for the dark fermentation processes. In the case of photosynthetic process, algae or some photoheterotrophic bacteria can be used for the H_2 production from CO_2 , H_2O , and organic acids (Karapinar Kapdan & Kargi, 2006). Cheese whey (Antonopoulou et al., 2008; Ferchichi et al., 2005), apple pomace (Wang et al., 2010), beer brewery wastewater (Vijayaraghavan et al., 2007), molasses (Tanisho & Ishiwata, 1994), and rice winery wastewater (Yu et al., 2002) are the examples for the valorization practices in the literature.

Although the clean and high energy content nature of hydrogen, the low yield, slow production rate and the necessity for large reactor volumes are the main limited factors and problems that more research and improvements need to be considered in this field.

2.7 Fermentation

Since food waste contains remarkable amount of starch, protein and lipids, the recovery of food wastes to supply carbon, nitrogen and phosphorous to biotechnological processes is one of the applications which are drawn attention nowadays. Hydrolysis of food waste by chemical or enzymatic methods to use it as a nutrient source for microorganisms is a promising approach to conduce the production of various chemicals and materials as well as energy (Pleissner & Lin, 2013).

Solid-state fermentation (SSF) which occurs on solid or semisolid substrates with nearly absence of free water is a traditional approach which refers to obtain a broad variety of chemicals and enzymes from various kind of food waste

(Couto & Sanromán, 2006). Citric acid production from apple pomace (Hang & Woodams, 1986), pineapple peel (Tran et al., 1998), sugar cane bagasse, coffee husk and cassava bagasse (Vandenbergh et al., 2000), lactic acid production from sugar cane bagasse (Soccol et al., 1994), ethanol production from apple pomace (Hang et al., 1982), the production of enzymes such as pectinases from fruit processing wastes (Zheng & Shetty, 2000), soy and wheat bran (Castilho et al., 2000), cellulose, xylanase, beta-glucosidase, and laccase from various crop residues (Pandey et al., 1999), alfa-amylase from banana waste (Krishna & Chandrasekaran, 1996), flavor production from coffee husk (Soares et al., 2000) and from agro-industrial solid wastes (Christena et al., 2000) are just a few examples for the application of SSF in the valorization of food waste.

Single-cell protein (SCP) which is based on a fermentation process on solid or liquid food wastes and after, harvesting of biomass manufactured by microorganisms was using for animal feeding in the beginning. But nowadays, the protein deficiency became an important problem for humankind and SCP starts to be evaluated as an alternative method for humankind nutrition as a protein supplement. Bacteria, yeast, fungi, and algae are the main sources for the production of SCP from biomass which have their own advantages and disadvantages. Bacteria is high in protein and have a rapid growth rate while having small size cells that create difficulty in harvesting, high nucleic acid and a negative overview of public. Yeasts have larger size cell, lower nucleic acid content, high lysine content and durability against acidic conditions while having lower growth rate, protein content, and methionine content. Fungi have also an easy harvesting but lower growth rate, protein content, and public acceptability. Finally, cellulosic cell wall and heavy metal concentrate are the main disadvantage of algae which has an intention not for sole protein but whole algal biomass in a form of pastilles, capsules, powder, and tablets (Nasseri et al., 2011). SCP production from citrus pulp (De Gregorio et al., 2002), pineapple waste (Dhanasekaran et al., 2011), cheese whey (Ghaly et al., 2005), extracted grape waste, and apple pulp (Kuzmanova et al., 1991) can be given as the example for SCP production.

2.8 Extraction

The molecular transport under a certain difference in chemical potential is the underlying principle of the extraction processes and equilibrium, material, and energy balances are the main factors that affect the extraction of target compounds from materials.

Soxhlet solvent extraction, steam distillation or hydro-distillation are the main applications which are generally employed very successfully in food industry for a very long time although they bring along certain disadvantages such as the using toxic and flammable solvents, time and energy consuming, the necessity for further separation/clean-up steps, and so on. But nowadays, the novel extraction strategies such as ultrasound-assisted extraction (UAE), pressurized liquid extraction (PLE), supercritical fluid extraction (SFE), microwave-assisted solvent extraction (MASE), accelerated solvent extraction (ASE), and solid-phase microextraction (SPME) are evaluated as promising techniques to overcome the disadvantages of traditional extraction methods (Walker et al., 2007, p. 242).

UAE is a technique which uses sound waves with a frequency higher than the range audible to humans and generally, the lowest ultrasonic frequency is taken as 20 kHz. Ultrasound can involve the expansion and compression cycles when traveling through a medium. In a liquid, the expansion cycle produces negative pressure and creates bubbles. When the bubbles grow and collapse in liquid where is close a solid surface, cavity collapse is asymmetric and produces high-speed jets of liquid which results in very strong impact on the solid surface and damages on the impact zones (Luque-García & Luque de Castro, 2003). UAE of bioactive chemicals from food wastes involving the extraction of polyphenols from orange peel (Khan et al., 2010), and apple pomace (Viot et al., 2010), hemicelluloses extraction from wheat straw (Sun & Tomkinson, 2002), and all-trans- β -carotene from citrus peels (Sun et al., 2011) can be given as examples for successful applications that enhances the extraction of target compounds compared with conventional extraction techniques.

SFE process is based on the contact of raw materials and pressurized solvent to remove the desired compounds from raw material to solvent. The extraction of these compounds from the solvent is realized by reducing the pressure. CO₂ is an ideal extraction solvent for this application because of the chance of the prevention the oxidation reactions and its ability of entering supercritical state under low temperature and pressure conditions. A supercritical fluid has a higher diffusivity because of possessing gas and liquid like properties together and this feature results in a rapid mass transfer and faster completion of extraction compared with traditional techniques (Walker et al., 2007, p. 219). But, a polar nature of CO₂ creates a disadvantage for polar analytes and the addition of a cosolvent such as ethanol is needed for the extraction of polar substances. The extraction of carotenoids from apricot pomace (Şanal et al., 2005), tomato processing wastes (Nobre et al., 2009;

Shi et al., 2009), the extraction of polyphenols from grape by-products (Casas et al., 2010), and orange pomace (Benelli et al., 2010) can be given as examples to the application of SFE.

Also, PLE is a technique that uses elevated temperature and pressure to enhance the solubility and mass transfer properties of the extraction procedure. The sample and desired compound type, the extraction type and mode, solvent, time, and temperature during the process and the use of enhancers are the main factors having an important effect on PLE technique (Mustafa & Turner, 2011). The possibility of automation which offers reduced extraction time and solvents may be the main reason for a wide range of application of this technique in food industry (Mendiola et al., 2007). The extraction of polyphenols from various by-products of plant origin is the main attempt for PLE application in the field of the valorization of high value-added compounds from food wastes (Wijngaard et al., 2012).

MASE technique involves the heating of solvent by microwave energy. As a result of this heating, the enhancing of the penetration of solvent into matrix and the solvation of components to be desired can be obtained by the disruption of hydrogen bonds via microwave-induced dipole rotation and migration of ions (Hudaiba et al., 2003). The industrial microwaves generally operate with a frequency at 2.45 GHz and the waves penetrate and interact with polar molecules (e.g., water) in the biomaterials to create heat. The dielectric susceptibility of solvent and matrix, the solvent volume and operational temperature are the important subjects must be considered during the MASE applications (Wang & Weller, 2006). Throughout the literature, MASE has been coupled successfully to steam distillation for the extraction of high value-added chemicals from food wastes. The extraction of essential oils (Ferhat et al., 2006; Sahraoui et al., 2011), D-Limonene and pectin (Pfaltzgraff et al., 2013) from orange peel, the extraction of phenolic compounds from potato processing wastes (Wu et al., 2012), and peanut skins (Ballard et al., 2010), the extraction of anthocyanins from grape skins (Liazid et al., 2011), the extraction of carbohydrates from the waste of corn starch production (Yoshida et al., 2010) represent the main implementations of MASE in the waste valorization literature. According to the studies, the reduced operational time and volume of solvent, and improved extraction yield are the common reasons to prefer MASE in the extraction procedures. However, the increase in temperature, microwave energy, and time must be taken into account during the process to avoid the generation of undesired compounds and degradation of desired compounds (Wang & Weller, 2006; Wijngaard et al., 2012).

Besides all these well-documented extraction methods, the new emerging techniques such as laser ablation, high-voltage electrical discharge, pulsed electric field, liquid membranes, and pervaporation have been suggested in the literature to overcome the disadvantages of conventional methods such as overheating, high energy consumption, loss in the activity of final products, and concerns about material safety for the extraction and recovery of valuable compounds from food wastes (Galanakis, 2012).

2.9 Chemical Conversion

Cellulose and hemicellulose which present into lignocellulosic biomass with a considerable amount involve primary C5 and C6 sugars and the dehydration of these sugars can produce important intermediate products such as furan chemicals (furfural and 5-hydroxymethylfurfural (HMF)). These intermediate products can play an important role in the production of high value-added chemicals and biofuels. The furan derivative chemicals such 2,5-furandicarboxylic acid, alkoxymethylfurfurals, 5-hydroxymethylfuroic acid, 2,5-dimethylfuran, levulinic acid, and so on are the chemicals that carry a very high potential for the production of polymers, pharmaceuticals, and fuels. (van Putten et al., 2013). The hydrolysis of glycosidic bonds in the carbohydrate to gain glucose units, isomerization, and transformation of glucose into fructose and the obtaining HMF via the dehydration process are the main route for arising of HMF. The acid catalyzed dehydration that involves the catalyzes such as mineral acids (HCl , H_2SO_4 , and H_3PO_4), organic acids (oxalic acid, levulinic acid, and maleic acid), Lewis acids, and so on, heterogeneous catalysts that offer a green chemistry, the use of inorganic salts and metal catalysts in the form of ions, salts or complexes can be used along the HMF production processes. These processes also use several reaction media such as aqueous, nonaqueous organic solvents, ionic liquids, supercritical solvents, and so on (Tahvildari et al., 2011). Although fructose and xylose lead to a high yield of HMF, the cost of these substrates can limit the application because of economic concerns. Glucose is a more favored option because of its low cost, but the conversion process needs two consecutive steps (isomerization and dehydration). However, xylose which a hydrolysis product of xylan and hemicellulose can be considered as a substrate for the one-pot transformation approaches (Zhou & Zhang, 2016).

Animal by-products such as hide, skin, animal fats, and protein rich meals can represent a main ingredient for a value-added

approach in the field of waste management. Blood meal, meat, bone, and chicken feathers meals can be converted into thermoplastic and thermosetting materials. Also, the protein obtained from animal by-products can be used for the development of wood adhesives, surfactants, and firefighting foams while the animal fat can be utilized in the field of biodiesel and oleochemical industries (Mekonnen et al., 2016). Biodegradable and edible materials, for examples biopolymers for packaging purpose and edible films, are another promising research fields for the valorization of plan animal by-products. Gelatin derived from fish and land animals and its potential for edible films and active packaging opportunities are one of the hot topics that draws attention among the researchers in the past years (Etxabide et al., 2016). Especially fish gelatin originated mainly from fish skin and bones shows similar rheological properties and thermostability to mammal gelatins and can find an application opportunity as an emulsifier, foaming agent, colloid stabilizer, hydrogel, and so on in the field of valorization practices (Gómez-Guillén et al., 2011).

3 Conclusion

The sustainability becomes a guiding strategy for societies while sustainable development is becoming an important goal for present and future generations via its certain effects on social, environmental, and economic progress. Food supply carries a vital importance for human survival. Nevertheless, the protection of natural resources which is tightly coupled with food supply is an inevitable priority in today's world. The fact of increasing soil, water and air pollution, deforestation, the decline in biodiversity and effects of climate change and in response to all these events, ever-growing human population and the needs for food and energy create a very serious problem to provide continuance of human survive. All these factors constitute certain unsustainability in the global agriculture and food systems, and the generation of huge amount of food waste became a major indicator of this instability.

Food industry has to produce enough food and ensure the food safety while giving rise to a less environmental impact. The improvement of food production efficiency, the prevention of food waste generation, and waste valorization for meeting the increasing demand for chemicals, materials, and fuel are the only solutions to restore this unsustainability. Appropriate waste management strategies including the prevention of unsustainable use of natural sources, huge amount of waste generation, and the

recommendation of a more cost-effective and environment friendly disposal system should be a global focus point which is shared by farmers, industrial producers, consumers, and policy makers.

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Further Reading

European Commission, 2010. Final Report—Preparatory Study on Food Waste Across EU27.

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FOOD WASTE RECOVERY: PROSPECTS AND OPPORTUNITIES

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1 Introduction

In 2016, a controversial article (Banerjee et al., 2016) was published about the prospect of utilizing milk of cockroaches as a super food in the years to come. This idea can only be considered as a joke in Europe and United States, but there are some other parts of the world (e.g., in China) where cooked cockroaches are actually an eating trend. According to this report, an international team of scientists sequenced a protein crystal located in the midgut of cockroaches because it is fourfold more nutritious compared to cow's milk and denoted that it may be the key to feed our growing population in the future. Although this idea looks disgusting for many readers, it is somehow reasonable from a scientific point and most of all it indicates the ultimate efforts of researchers to look for alternative food sources. Besides, the urgent need for sustainable food systems is increasing day by day.

Earlier, in 2011, Food and Agricultural Organization (FAO) published a report considering global food losses and food wastes noting that nearly one-third of worldwide food production (1.3 billion ton/year) for human consumption is lost or wasted. The amounts of food loss and waste along the food supply chains, respectively, are 54% of total loss and waste as upstream processes (including production and postharvest) and 46% of total loss and waste as downstream processes (including processing, distribution, and consumption) (FAO, 2011). The European Commission technical report (published in 2010) indicated that around 90 million

tonnes of food wastes are generated within European Union (EU) each year. The percentage breakdown of food wastes according to this report is 39% manufacturing, 42% households, 14% food service/catering, and 5% retail/wholesale (2006 EUROSTAT data and various national sources provided by EU Member States). Based on this study, it is expected that food wastes would reach 126 Mt in 2020 (from about 89 Mt in 2006), without additional prevention policies or activities. From 2006 up to 2020, food waste tonnages are expected to be 3.7 million in EU27 when population increases by nearly 21 million (Ottles et al., 2015).

So why not taking care of these tonnages of wasted foods first before discussing about other controversial options? Are all of these wasted foods edible? Of course, it is difficult to recover household food wastes and expect to redistribute it in proper and healthy meals. But there are really many waste streams (e.g., fruit processing by-products, ugly fruits, foods that are about to expire soon, etc.) that do not lack at all of nutritional and sensory characteristics compared with fresh foods (if producer does not allow them to spoil). For instance, phenols and carotenoids could be recovered from fruit peels prior being utilized as natural food or beverage preservatives (Galanakis et al., 2015a,b; Heng et al., 2015, 2016). Recovered pectin from apple and olive pomace (Galanakis, 2012; Galanakis et al., 2010a,d; Roselló-Soto et al., 2015a) or β -glucan from oat mill waste (Patsioura et al., 2011) could be utilized as gelling agent in confectionary or as fat replacement in meat. Water insoluble fibers (e.g., hemicelluloses from cereal processing by-products) are able to improve intestinal regulation and thereby are destined to supplement food products or ready meals. Cheese processing whey is an abundant source of lactose and proteins, and thus it is designated for the delivery of monosaccharides and oligopeptides in nutritional supplements and soft drinks, respectively (Galanakis et al., 2014a). Protein hydrolyzates from fish by-products have also been proposed as seafood flavors for soups or surimi.

2 The Distance Between Food Wastes and Food By-products is Connected With a Road Called “*Recovery*”

Until the end of the 20th century, disposal of food wastes was not considered as a matter of concern. Particularly, increase of food production without improving the efficiency of the food systems was the prevalent policy. This consideration increased generation

of wasted food along supply chains. In the 21st century, escalating demands for processed foods have required identification of concrete directions to minimize energy demands and economic costs as well as reduce food losses and waste. Today, food wastes account as a source of valuable compounds and deal with the prospects of feeding fast growing population. Perspectives originate from the enormous amounts of food-related materials (food “losses,” “wastes,” “by-products,” or “wasted by-products”), which are discharged worldwide and the existing technologies that promise not only the recovery but also the recycling and sustainability of valuable ingredients inside the food chain (Galanakis, 2012).

2.1 Definitions of “Food Waste” and “Food Loss”

Food supply chains begin from the primary agricultural phase, proceed with manufacturing and retail, and end with household consumption. During this life cycle, food is lost or wasted because of technological, economic, and/or societal reasons. The definitions of “food waste” and “food loss” within the supply chain have been a subject of disagreement among the related scientists.

According to the EU Commission Council [Directive, 2008/98/EC](#), “waste” is defined as “any substance or object, which the holder discards or intends or is required to discard.” According to the Foresight Project report prepared by The Government Office for Science (GO-Science) ([Foresight Project, 2011](#)), food waste is defined as “edible material intended for human consumption that is discarded, lost, degraded or consumed by pests as food travels from harvest to consumer.” In July 2014, the European Commission has announced its targets for the circular economy, waste management and provided a “food waste” definition as “food (including inedible parts) lost from the food supply chain, not including food diverted to material uses such as biobased products, animal feed, or sent for redistribution” (i.e., food donation).

“Food loss” refers to quantitative and qualitative reductions in the amount and value of food. The qualitative loss corresponds to the loss of caloric and nutritive value, loss of quality, and loss of edibility. Quantitative loss refers to the decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for human consumption. [FAO \(2014\)](#) global voluntary definitional framework defined “food loss” as the decrease in quantity or quality of food, caused mainly by food production and supply system functioning or its institutional and legal framework. Thereby, “food loss” occurs throughout the food supply chain. Moreover, FAO distinguishes “food waste” as an important part

of “food loss,” which refers to the removal of food from the supply chain, which fits for consumption by choice or has been left to spoil or expire as a result of negligence (predominantly but not exclusively) by the final consumer at household level.

2.2 Prospects

According to [FAO \(2014\)](#), a management strategy for resource optimization via waste reduction at source is producing the greatest benefit to the food processing industries and society. Moreover, recent changes in the legislative frameworks, environmental concerns, and increasing attention toward sustainability have stimulated industry to reconsider the concept of “recovery” as an opportunity. This prospect has changed the way we are considering food loss and food waste. Today, all the food-related substrates, which are lost within the food supply chain (food loss), should be primarily considered as by-products. The latter could be valorized directly for nutritional purposes or used as raw materials for the recovery of valuable ingredients and compounds. In both cases, food waste includes all the remaining substrates from these processes that are finally not consumed and discharged. This concept generates two simple approaches as stated by Food Waste Recovery Group (www.foodwasterecovery.group):

$$\text{Food Losses} - \text{Reutilized By} - \text{products} = \text{Food Waste} \quad (1)$$

$$\text{Food Waste} = \text{Wasted By} - \text{products} \quad (2)$$

2.3 The Term “Food Waste Recovery”

The potential of food wastes to create new opportunities and markets has been underestimated until the very recent years. Indeed, the term “Food Waste Recovery” was not in use, whereas the term recovery was used to underline the prospect of reutilizing or valorizing food waste somehow.

The term “Food Waste Recovery” was established by the Special Interest Group of ISEKI Food Association (FA) in 2012 (<https://www.iseki-food.net/general/sigs/sig5>). It was used as an abbreviation for the expression “extraction of valuable compounds from wasted by-products.” The main difference between the widely used term “Food Waste Valorization” and “Food Waste Recovery” is that the second expresses the reutilization of food losses in a quantitative and qualitative manner within food chain. Indeed, Food Waste Recovery targets to upgrade compounds and ingredients lost within food waste streams by creating high

value-added products (e.g., functional foods). Until now (March 2017), Food Waste Recovery Group of IFA has developed a number of teaching tools (e.g., a reference module, books, a webinar series, an e-learning course, etc.), research activities (Deng et al., 2014; Zinoviadou et al., 2015; Barba et al., 2015; Roselló-Soto et al., 2015a,b; Belaqziz et al., 2016), and other actions (e.g., open innovation network) aiming at helping food industries and other involved partners in the food chain to recover valuable compounds from food waste, valorize their streams, and improve their sustainability.

3 Food Waste Recovery: Time for Industrial Implementation

The industrial recovery of recovering valuable compounds from food by-products is a story that started few decades ago. Citrus peel was one of the first by-products to be utilized for the recovery of essential oils and flavonoids and their reutilization as additives and flavorings in foods and fruit juices. Even earlier, solvent extraction had been applied to recover oil from olive kernels, which are one of the by-products derived from olive oil production (Galanakis, 2011). Nowadays, olive kernels are considered as an established commodity similar to olive fruit, whereas researchers focus on the recovery of polyphenols from olive mill wastewater (Rahmanian et al., 2014). Over the last decade, several companies have started commercializing the latest process and are ambitious to turn this waste into valuable compounds. In the field of animal-derived side streams, cheese whey constitutes the most intensely investigated food by-product and represents a successful reference of valorization. Protein concentrates and various sugar derivatives are the prominent compounds derived from this source, as reflected by the numerous processes and products exist in the market. Today, at least 50 companies around the world recover valuable compounds from food waste and sell them as clean label ingredients for processed food products (e.g., natural preservatives to maintain shelf-life requirements, functional compounds), without impacting flavor or texture (Galanakis and Schieber, 2014; Galanakis et al., 2016).

These commercially available applications inspired the scientific community to intensify its efforts for the valorization of all kinds of food by-products for recovery purposes. Besides, the perpetual disposal of high-nutrient proteins, antioxidants, or dietary fibers in the environment is a practice that could not be continuing for a long time within the sustainability and bioeconomy

frame of the modern food industry. Indeed, the depletion of food sources, the fast growing population, and the increasing need for nutritionally proper diets do not allow considering other alternatives (Galanakis, 2015a,b). As a result, a large number of projects have been initiated all over the globe and across scientific disciplines, whereas the existence of numerous scientific articles, patents, congresses, and industrialization efforts have emerged a wealth of literature in the field. Despite this plethora of information and the developed technologies, the respective shelf products remain rather limited. For instance, only few companies across the globe are activated on this field, whereas many of them are in an early stage and have not developed their process in a commercial manner yet (Galanakis, 2012; Galanakis and Schieber, 2014). This is happening because the industrial implementation of food waste exploitation for the recovery of valuable components is a complex approach that needs careful consideration of numerous aspects (Galanakis, 2015a,b).

4 Innovation Barriers, Challenges, and Solutions

Nowadays, the term “*innovation*” is increasingly used in all science fields. It has been developed into a trendy word that is referred whenever discussions focus on forthcoming developments or future perspectives. Nevertheless, despite its frequent usage, innovation is neither easy to specify and nor to identify. What does innovation truly represents? It is a new idea that when implemented leads to a more effective process, product, service, or technology. Innovation provides better solutions that meet advanced, unaddressed, or existing market needs. It can be considered as a breakthrough that provides a different way of thinking, consuming, or living. However, the key element of innovation is the precondition noted above: “*when implemented*.” Without implementation, “*innovation*” turns back to the “*idea*” status.

Food industry is facing technical and economic changes in spite of society, manufacture, and food processing. This fact has affected significantly the entire food supply chain (e.g., distribution of food to the consumers), forcing companies to pay high attention in food products that meet the consumers’ demand for a healthy lifestyle. As a consequence, there is an extensive dialog about the need of food industries to introduce innovations in the market to survive competition.

Innovations have been discussed not just as an opportunity but also as a precondition to assure the sustainability of the food sector.

It is an important instrument to stand out competition and satisfy consumer demands. Ultimately, it is the tool to success in a hard economic environment, the carrier to penetrate new markets, and the key to establish new products or processes. On the other hand, food industry is traditionally considered as a sector with low research intensity. Although researchers develop continuously innovative products and technologies, their applications in the food industry meet several obstacles. The latest fact concerns more about the introduction of the innovations within the food industry as well as the reaction of related consumers and less about the technological adequacy of the innovative techniques. Indeed, there is a gap between R&D strategy developers and technical R&D associates, as well as a lack of interpretation between the information received by food technologists and consumer scientists.

Food waste recovery is among the cutting-edge areas of the food industry. The development of sustainable innovations in this field starts by dealing with long-term R&D issues (e.g., networks development, open innovation, the role of innovation policies, etc.) and technical aspects (e.g., conventional versus emerging technologies) prior identifying resistance issues and designing strategies that meet the needs of the food industry.

To this line, the industrialization of food waste recovery processes includes numerous issues such as laboratory research, transfer to pilot plan and full-scale production, protection of intellectual properties, development of definite applications, commercialization problems, and in some cases approval of products' health claims. These issues are necessary to ensure the sustainability of the process, the economic benefit for the involved food industry, and the perpetual establishment of the derived products in the market.

For example, waste emerges seasonally and often in large quantities, whereas it is prone to microbial spoilage. Therefore, waste collection in the source is a critical problem that often requires additional transportation cost and control of microbial growth. Proper management of collection process, cooling/freezing of the material, and/or addition of chemical preservatives can provide solutions at the particular case. Another complicated problem is the broad variation of target and nontarget compounds from source to source. This fact affects the mass and energy balances as well as the functionality and the organoleptic character of the final products, especially in the case of more crude extracts. The above problem may be modified by adding a pretreatment step. Besides, scale-up of recovery processes meets the same limitations as any food manufacture procedure. Transition of batch to continuous processes is usually

accompanied with extension of mixing and heating time, heavier handling, increased air incorporation, and higher degree of scrutiny. All of these parameters generate numerous interactions and loss of product's functionality. Subsequently, process cost is increased, as industrially recovered compounds are used in food formulations in higher concentrations compared to laboratory-recovered compounds.

A commercially feasible product can be generated only if a certain degree of flexibility and alternative choices can be adapted in the developing methodology. Thereby, methodologies with less recovery steps are cheaper and scale-up easier, but at the same time, they generate cruder products with lower concentrations of target compounds. Likewise, the implementation of nonthermal technologies and addition of green solvents and safer materials (possessing GRAS-status) are strongly recommended. Besides, experience has shown that a project focused on the recovery technologies without investigating and establishing particular applications is doomed to fail because the final product might not be as beneficial as initially expected (Galanakis, 2012). On the other hand, safety assessment and market release permission of purified active compounds are very demanding. This procedure includes long and sophisticated tests on different species of laboratory animals (similarly to synthetic antioxidants). In the case of enriched natural extracts, the criteria are not so strict. This is happening because natural extracts are considered to exist inherently in foods and thus safety concerns are limited.

In another point of view, innovations in the field are driven by spin-off or start-up companies, which were usually created by researchers. These companies are considered as small and medium enterprises (SMEs), although in most cases are even smaller (microenterprises). These companies are struggling to implement innovations due to limitations and numerous barriers, such as the lack of adequate collaborations, the minimal external experience (competition), and the limited financial resources for internal research and development. Finally, developments in the chain's environment, such as the availability of new technologies or restrictions imposed by governmental and supra-governmental legislation, can also trigger innovation efforts.

In addition to these challenges, the product to be developed needs to meet the high expectations of the consumers in an increasingly competitive market. Today, consumers are more aware of risks confronting them and increasingly display a preference for natural entities, which have been generated without human intervention. In addition, they require environmental-friendly food products that are closely tailored to their individual preferences and well-being. These aspects support the promotion of the

so-called “green” marketing and quality assurance concepts, for example, as “organic” and “Protected Designation of Origin” products. The food safety concerns, the health risks, the complexity of globalized food chains, and the depletion of food resources create a challenging environment for food innovators. The commercialization of processes dealing with the recovery of valuable compounds from food wastes does not comprise an exception, as it faces important challenges that need integrated solutions.

Besides, regulatory issues still exist and constitute a severe problem for the industry. On one side, without doubt there is a market need for nutraceuticals and functional foods. On the other hand, marketing of such products using health claims requires comprehensive research activities to unambiguously demonstrate their health benefits. Authorities around the world have tightened up the way in which companies can advertise health benefits. In the case of EU, health claims have been approved for a small number of compounds (e.g., hydroxytyrosol in olive oil). Thereby, if you recover hydroxytyrosol from olive mill wastewater and fortify foodstuff (e.g., bakery products) or even olive oils, you are not allowed to use the health claim on the label. This policy is driven by the need of protecting consumers from dubious claims. Nevertheless, demonstration of proven health benefits is very costly for the companies activated in the field, constituting an impediment especially to small and medium-sized, spin-off and spin-out companies. This fact creates implications and stifles innovation in the field, as the obtainment of the required data too costly and most companies (typically start-ups with low funding) cannot afford them. So far, only a small number of compounds and products have been approved, whereas the overwhelming majority of health claims has been declined by regulatory bodies (Galanakis et al., 2016). Therefore, the risk of claims rejection by the corresponding authorities is too high.

To prevent stifling of innovation in the field from the strict regulations and accelerated safety concerns, and simultaneously address emerging wellness aspects, a new direction for developing and implementing scientific breakthroughs is required. In particular, the legislation challenges regulating health beneficial dietary products are lying to the specificity of the products, which have the characteristics of both food and biologically active ingredients. Thus, it would be advisable to clearly define the manufacturing and quality control criteria related to composition and content range of active substances as well as manufacturing development of the product (Galanakis et al., 2016). Currently, the manufacturer's label typically provides only limited information about the origin and composition of the used extract in the final product formulation. A clearer label of the products containing recovered

compounds would enable nutritionists and/or pharmacists to be more confident when recommending these products. In addition, developing an industrial “open innovation” effort is of high priority and should be considered in the case of food waste recovery projects. At this case, all participants (university, industry, government, and private sector) need to take a proactive role. For instance, since the policy of food waste reduction is among the high priorities in the agenda of governmental and supra-governmental bodies around the world, alternative ways out should be provided (e.g., reduced taxes or the establishment of a new label) to reveal the potentiality of recovering high value-added ingredients from food by-products and reutilizing them inside food chain. This label could be relevant to organic foods or similar to carbon emission labels or ecological footprint labels (Galanakis et al., 2016).

On the other hand, it is very important to provide clean label ingredients for processed food products (e.g., natural preservatives, functional compounds), without impacting flavor or texture and while maintaining minimum shelf-life requirements. The development of the production line should be designed near, but not inside the food industries, to ensure minimum transportation and at the same time meet their Hazard Analysis and Critical Control Point (HACCP) requirements. The final product should be precisely designed for a well-defined market, too. For instance, natural antioxidants to be used in fresh, mom-approved and kid-friendly foodstuff with clean ingredient lines and a minimum of 3-month refrigerated shelf life. Unlike the needs to delight the consumer and minimize environmental impact, developers should also ensure that the final product and process meet particular specifications, as well as they are ready for commercial production. Modern new products should aim at the fulfillment of consumer needs and the realization of consumer value rather than at the development of products or enabling technologies per se. This is important to state due to the recently opened debate concerning the safety of products recovered from food wastes and the impact (beneficial or not) of recycling them inside food chain (Galanakis, 2012).

5 Conventional Versus Emerging Technologies

Energy efficiency of conventional techniques is not so high and respective cost is not low enough to extract compounds that exist in lower concentrations inside by-products compared to the

initial substrate (e.g., whole fruits or vegetables). In addition, traditional thermal processes such as concentration, drum, or spray drying may cause enzymatic or nonenzymatic deterioration of the target compounds, loss of their functionality and diminution of the final product's organoleptic characteristics. In many cases, conventional extraction is restricted due to the nonfood grade nature of the used solvents. Target compounds such as antioxidants may not be stable in the shelf due to the inefficient encapsulation of the final product. Besides, consumers are and always will be skeptical about the safety of products derived from by-products or food wastes.

The yield of the applied technologies, the scale-up boundaries, the safety of the final products, and the overall cost are the most important parameters governing the industrialization of recovery processes. Nowadays, improving process efficiency during food manufacturing focuses on minimized cost. The latest is typically conducted by reducing processing steps, enhancing throughput, restricting overall energy consumption, and optimizing plant design. Emerging and typically nonthermal technologies (e.g., radio-frequency drying, electroosmotic dewatering, cold plasma treatment, high-hydrostatic pressure, ultrasound-assisted extraction, laser ablation, high-voltage electrical discharge, pulsed electric field, nanoencapsulation, etc.) promise to overcome the obstacles of conventional techniques by claiming increased recovery yield and reduced processing time, optimized heat and mass transfer that results in lower operation cost, gentle treatment of food waste matrix and control of unwanted Maillard by-products, and advanced encapsulation and ultimately improved functionality of antioxidants (Galanakis, 2013).

Despite these promising advantages, the implementation of emerging technologies in the recovery downstream processing is still under debate. Emerging technologies possess not only advantages but also disadvantages that concern mainly the product safety, especially in the case of the most advanced techniques. For example, the cells membrane permeability of cold plasma or nanotechnology and their effect on biological matrices remain uninvestigated yet. Other emerging technologies may be too sophisticated for their implementation in the field, as they require high capital cost and energy overconsumption compared to the additional value induced by the increase in the extraction yield.

In any case, researchers and professionals of the food industry will soon deal with the prospect of applying emerging technologies and particularly nanotechniques with an ultimate goal to optimize the overall efficiency of suggested methodologies. Besides, the market and consumers demand for tailored-made

products will lead producers to adapt sooner or later some of these technologies. This status will reopen debate concerning the safety of products recovered from food wastes and the impact (beneficial or not) of recycling them inside food chain. Further research on the field would supply technical feedback to reduce operation cost and set up minimal processing. Likewise, it would provide safety assessments to establish methodology and satisfy consumer claims for healthier and tastier products.

6 The *Universal Recovery Strategy* and How to Implement It

Food wastes are generated in different forms and compositions following the regional, seasonal, and processing characteristics in each case. Moreover, they generally contain lower concentrations of valuable compounds compared to the initial sources (e.g., fruits or vegetables). This fact results in higher processing cost, lower recovery yield, and ultimately lower revenues. Food wastes are already processed materials, susceptible to microbial growth, and require both preservation and fast treatment. Thereby, collection in the source is crucial, and extended transportation should be avoided. Following the above considerations, the development of an economic feasible, sustainable and safe recovery of high value-added compounds from food wastes requires a holistic approach, taking into account parameters such as:

- a. waste minimization prior recovery processing,
- b. the abundance and distribution of the food wastes in the source of their production (typically food industries),
- c. the proper collection and mixing of food wastes to minimize variations in the content of their components (this way variations in the final products are avoided, too),
- d. the development of a production line near but not inside the food industries to ensure minimum transportation and at the same time meet their HACCP requirements,
- e. the development of a methodology that provides the highest recovery yield of different compounds and discharges minimum quantities of by-products in the environment,
- f. the nondestructive separation of valuable compounds, their recapture in different streams, and their reutilization in different products,
- g. the addition of food-grade materials and the utilization of green solvents,
- h. the proper management of the selected stages and technologies,

- i. the preservation of the compounds' functional properties from the source to the final product, and
- j. the development of qualitative products with constant concentration of target compounds and stable sensory characteristics.

Fig. 1 illustrates the “Universal Recovery Strategy” that was presented for the first time in Chapter 3 of the book “*Food Waste Recovery: Processing Technologies and Industrial Techniques*” (Galanakis, 2015a,b). Initially, the different forms and compositions of wastes exist for a particular source (e.g., a fruit or a vegetable) are identified. The next step is to collect all the necessary information concerning food waste availability,

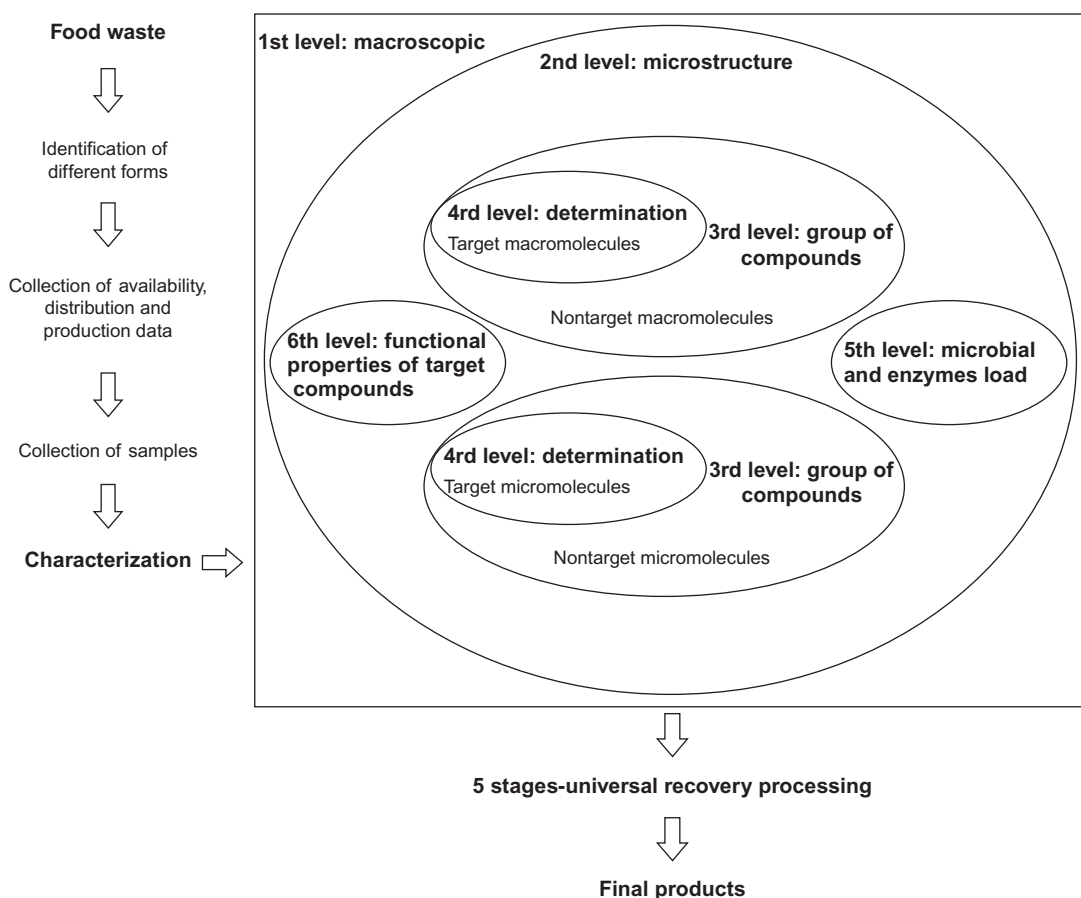


Fig. 1 The universal recovery strategy. Adapted from Galanakis, C.M., 2015. Preface. In Galanakis, C.M. (Ed.), *Food Waste Recovery: Processing Technologies and Industrial Techniques*; Galanakis, C.M., 2015. Chapter 3: Development of a universal recovery strategy. In: Galanakis, C.M. (Ed.), *Food Waste Recovery: Processing Technologies and Techniques*, Elsevier Inc., Waltham.

distribution in different locations, production frequency (e.g., seasonal or not), and finally generated quantities. Not all these data may look like particular interest for the development of the recovery processing, however, they are necessary in business plans that evaluate the overall potentiality and economic growth of the developed process. Thereafter, samples are collected and characterized in six levels.

The first one includes the determination of macroscopic characteristics, for example, the different phases (water, oils, and solids) within waste mixture. The adjustment of the phases' content could be an effective way to fit in the different compositions of the initial substrates. The second level is the determination of microstructure characteristics to get an overview of waste matrix prior designing the recovery process. The third level is the determination of compound groups, namely, total phenols, total sugars, carotenoids, dietary fibers, proteins, etc. This step allows having a clear view of main macro- and micromolecules content prior designing their separation. Besides, these determinations (typically based on spectrophotometric techniques) allow the fast screening of numerous samples and optimization conditions. The fourth level of characterization is the identification of particular target macro- and micromolecules. A fifth level of characterization should be the determination of microbial and enzyme load. The latest cause deterioration of the substrate and in many cases can diminish the functional properties of target compounds (sixth level of characterization). For example, enzymes such as pectin methyl esterase, pectic lyase, and polygalacturonase of fruits by-products can affect pectin deesterification and solubilization during processing. Besides, polyphenoloxidases can diminish the antioxidant properties of polyphenols (Galanakis et al., 2010b,c). The final step of the recovery strategy is the so-called “5-Stage Universal Recovery Process” that is illustrated in Fig. 2 (adapted by Galanakis, 2012). This downstream scheme is selected if at least two different components are recovered or the valuable component is a micromolecule (e.g., antioxidant). However, steps are often eliminated or oversubscribe each other, for example, for macromolecules (e.g., pectin), the second stage could be omitted.

Processing moves from the macroscopic to the macromolecular level, prior the extraction, the clarification, and the encapsulation of target compounds in a final product. The macroscopic pretreatment aims the adjustment of the food waste matrix according to the water content, enzymatic activity, and permeability of the bioresource tissues. If the substrate is a wastewater (e.g., of olive oil industry), concentration is utilized with a final

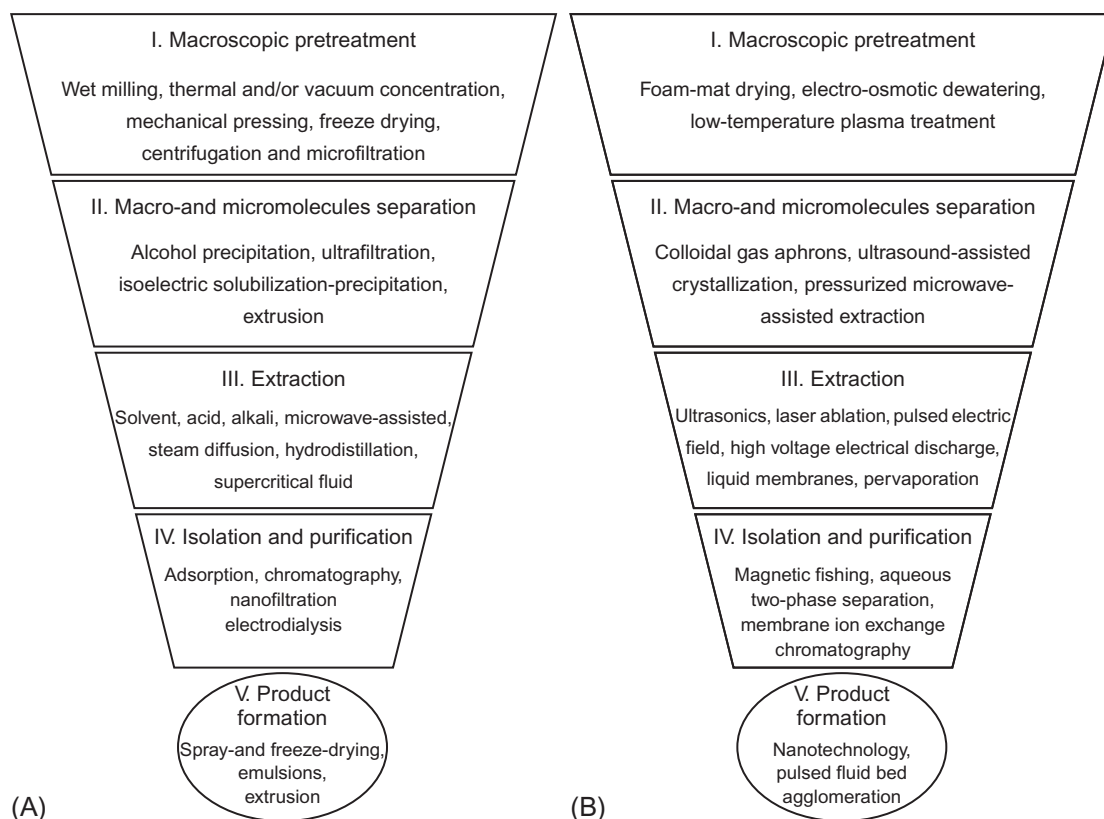


Fig. 2 The “5-stage universal recovery process.” (A) Conventional Technologies, (B) Emerging Technologies. Adapted by Galanakis, C.M., 2012. Recovery of high added-value components from food wastes: conventional, emerging technologies and commercialized applications. *Trends Food Sci. Technol.* 26, 68–87.

purpose of removing water and increasing the content of valuable components. Thermal concentration causes activation or deactivation of key enzymes (e.g., polyphenol oxidase), whereas athermal processes (e.g., freeze drying) possesses other disadvantages such as increased cost due to the presence of vacuum conditions. Alcohol precipitation is the most popular method for the separation of smaller compounds (e.g., antioxidants) from macromolecules (e.g., dietary fiber). This method is selected because it is cheap, nontoxic, and easy to use. However, it is neither selective nor able to separate the complexes between the smaller and the larger molecules. Extraction is the important stage of downstream processing, and different techniques may be employed toward the target molecules and their physicochemical characteristics. Solvent extraction is very convenient, as the solvent provides a physical carrier to transfer the target molecules between different

phases. In addition, it can be performed in combination with pressurized and distillation processes, which accelerate the process and extract volatile compounds, respectively. Among the several solvents, ethanol is often preferable because it is cheap and has a food grade nature (Tsakona et al., 2012; Galanakis et al., 2013a). On the other hand, supercritical fluid extraction is employed for difficult separation processes of valuable compounds with low quantity. The clarification of target compounds from co-extracted impurities could be conducted with several methods such as resin adsorption. Nanofiltration has also been suggested for the clarification of a phenol containing beverage derived from olive mill wastewater by removing polymerized phenolic fractions. Finally, product formation (e.g., of antioxidants) is performed using encapsulation techniques that are able to entrap bioactive food components inside a coating material, and this way to preserve their stability. In the case of recovering polysaccharides, dietary fibers, or proteins, encapsulation stage is replaced with spray drying. Other nondrying methods such as liposome and emulsion entrapment are typically used to entrap lipophilic bioactive compounds (Galanakis, 2016). The implementation of the *5-Stages Universal Recovery Process* for the recovery of (i) phenols and pectin from apple pomace, (ii) antioxidants and dietary fibers from olive mill wastewater, (iii) chlorogenic acid, caffeine, melanodins, and dietary fiber from coffee silverskin, and (iv) lactose and different proteins from whey have been referred in details by Galanakis et al. (2015a,b).

7 Food Waste Recovery as a Tool to Improve the Sustainability of Food Systems

A food system is defined as the sum of all the diverse elements (environment, people, inputs, processes, infrastructures, institutions, etc.) and activities related to the production, processing, distribution, preparation and consumption of food, and their socioeconomic and environmental outcomes (HLPE, 2014). Sustainability is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. However, this definition is difficult to be understood or applied by organizations that have specific responsibilities to the society, beyond their economic and legal obligations. Nowadays, organizations and specifically food production systems can no longer ignore the need to act in a sustainable way. Food products must be politically, economically, environmentally, socially, and technologically sustainable (Beer and Lemmer, 2011). Thereby,

the relative organizations have specific responsibilities to the society that go beyond their economic and legal obligations. To this line, dealing with their impact on all off the involved stakeholders (i.e., shareholders, employees, customers, suppliers, etc.), organizations can achieve long-term profitability.

Today, there is a need to identify ways to best utilize discharged food materials. Reducing processing food wastes by recovering valuable compounds and developing new products can significantly improve the sustainability of the food production system. For example, reductions in energy and raw material usage can reduce costs and simultaneously increase the environmental performance of the food system. This will be achieved through the efficient use of the materials and energy used for production. With food waste recovery, the efficient use of materials has two meanings: (i) valorizing the material that otherwise will have been discharged and (ii) processing that material in an efficient way (Otles et al., 2015). For example, cheese processing whey is a by-product that could be used to recover sweeteners, prior their implementation in nutritional supplements. Through the recovery of those valuable materials, high energy savings can be achieved. This process could enable compliance with different types of food regulations, which are used to check regulatory compliance of other food products. For example, the water insoluble fiber could improve intestinal regulation and consequently could be used to supplement food products or ready meals. Thereafter, economic benefits could be achieved since the need to buy ingredients or develop new products that does not exist. In conclusion, food waste recovery improves substantially the sustainability of food systems, and this way is the new trend in food science and technology.

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